SHAPING AND CLEANING IN ENDODONTICS

By

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Thesis

Submitted to

University Of Liverpool

In partial fulfilment of the requirements for the

Degree of

Doctor of Dental science in Endodontics

September 2017

Abstract

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Introduction: Root canal instrumentation is a challenging procedure, due to different factors. These factors can be related to tooth anatomy, operator skills and experience and instruments used during the treatment. Certain areas regarding operator experience and root canal instrumentation in the endodontics literature are still not fully understood and are in need of further research.

Aims: The aim of this thesis was to review the available literature on root canal instrumentation. The two main aspects investigated in this thesis, are operator experience and its effect on procedural errors during root canal instrumentation and the ability of rotary nickel titanium instruments in achieving three-dimensional instrumentation of the root canal system using modern instruments that can conserve the tooth structure.

The objective of the 1st study is to investigate the procedural errors created and time efficiency of modern engine driven rotary endodontic file systems used by inexperienced users.

The objective of the 2nd study was to investigate the percentage of root canal surface instrumentation and amount of dentine preservation achieved by a recently introduced endodontic file system claimed to achieve higher percentage instrumentation of root canal walls, whilst conserving tooth structure.

A second objective of this study was to investigate the instrumentation effect of XP-endo finisher (XPF) rotary NiTi file at the end of preparation sequence on the percentage of root canal wall instrumentation, following the use of XP-endo Shaper (XPS) file system compared with ProTaper Next (PTN) file system.

Methodology: The evidence present in the literature regarding the effect of the operator experience on the amount of procedural errors created during root canal preparation and the efficacy of instrumentation of the root canal walls was reviewed and is presented in Chapter 2. The literature was searched using google scholar, PubMed and web of Science and a narrative review was completed.

An *in vitro* crossover randomised double blinded trial, using ProTaper Universal (PTU) or ProTaper Next (PTN) rotary nickel titanium (NiTi) files, to prepare simulated root canals by undergraduate dental students was conducted at the school of dentistry at University of Liverpool and is presented in Chapter 3.

In vitro randomised single blinded trial was conducted to investigate the ability of instrumentation and conservation of tooth structure of two file systems XP-endo Shaper (XPS) rotary NiTi file and ProTaper Next rotary (PTN) NiTi file in 24 extracted mandibular molars, using Micro Computed Tomography (μCT) imaging and three dimensional analysis.

Results: The literature revealed some gaps in knowledge regarding the effect of operator experience on the number of procedural errors produced during root canal preparation with some rotary file systems. There was a lack of evidence of recently introduced rotary file systems and its ability to instrument the root canal system.

The 1st study, showed that the PTN file system was better than the PTU in producing successful preparations in a shorter time than PTU in undergraduate hands.

The XPS file system demonstrated better ability to instrument the canal walls, with a higher percentage canal wall contact compared with the PTN. XPS files were more conservative of the root dentine than PTN. XPF also showed improvement in the percentage of canal wall instrumentation as a finisher file at the end of the preparation without removing a significant amount of root dentine.

Conclusions: In the hands of novice operators, PTN showed a lower incidence of procedural errors and better time efficacy during instrumentation of simulated canals compared with PTU.The XPS file system achieved high percentage of root canal wall instrumentation whilst preserving root canal dentine. Using XPF file as a finisher file after any rotary file system improves the percentage of mechanical instrumentation without a significant effect on the amount of dentine removed.

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Acknowledgment

To my beloved family for their everlasting love, support, encouragement & continuous prayers. I am thankful to them for trusting and believing in me.

I am most thankful to God for all his kindness, grace and blessing for giving me the patience and enthusiasm to accomplish this work.

It has been a great honour to undertake this research under the supervision and support of Dr Antony Preston, Senior Clinical Lecturer in Restorative Dentistry and my primary supervisor, Dr Fadi Jarad, Senior Clinical Lecturer in Restorative Dentistry, my Programme Director and secondary supervisor and Miss Katherine Blundell, Clinical Teacher in Restorative Dentistry and my third supervisor. I would like to express my gratefulness and appreciation for their continuous support and guidance.

Special thanks to Dr Jarad for believing in me and my abilities to accomplish this piece of work and for showing me the way, by his patience, generous support and valuable advice.

In addition I would like to thank Mr Girvan Burnside, Senior Lecturer in Biostatistics for helping me with and teaching me statistics, through the journey of my research.

Also not to forget to thank Prof Rob Van 'T Hof and Miss Gemma Charlesworth from institute of chronic disease at University of Liverpool, for helping me and giving me the chance to use the Micro CT scanner.

Finally, I would like to acknowledge all my friends and colleagues, especially the ones from the DDSc. Program and from the Restorative Department at Liverpool University Dental Hospital.

Structure of thesis

The following is a brief overview of the subsequent chapters in this thesis, highlighting the main objectives:

Chapter 1: Introduction: This chapter presents a definition of endodontology, the aim of root canal treatment and its main aspects. How the treatment was undertaken historically and how it developed and to identify the challenges faced.

Chapter 2: Literature review: This chapter presents a broad overview of the academic insights and evidence found regarding endodontics.

Chapter 3: First study: This chapter presents the 1st study conducted as a part of this thesis, investigating effect of operator experience on procedural errors.

Chapter 4: Microcomputed tomography and image analysis: This chapter presents a brief view of micro-CT and imaging technology, showing how it works, challenges and what can be investigated using this technology.

Chapter 5: **Second study:** This chapter presents the 2nd study conducted as a part of this thesis, investigating the ability of instrumentation of a recently introduced file system.

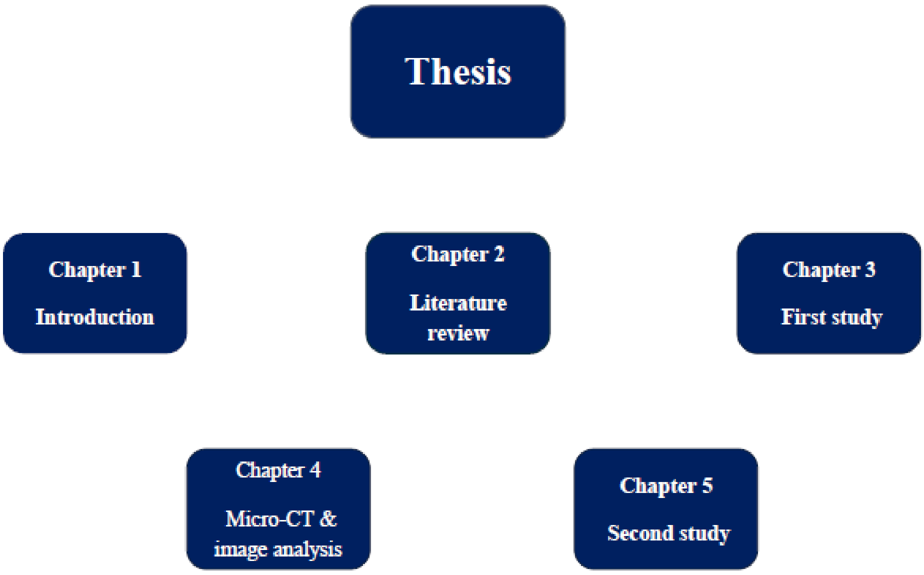


Figure 1: illustrating the structure of the thesis and different chapters.

Chapter 1: Introduction

“Endodontology is concerned with the study of the form, function and health of, injuries to and diseases of the dental pulp and peri-radicular region, their prevention and treatment; the principle disease being apical periodontitis, caused by infection” European Society of Endodontology (ESE, 2006) The aetiology and diagnosis of dental pain and diseases are integral parts of endodontic practice. The causes of endodontic problems are either inflammation or infection of the dental pulp. When the dental pulp is insulted or injured the aim of the treatment is to protect and preserve the healthy peri-radicular tissue. When the infection extends to the periapical tissues, apical periodontitis occurs, the aim of endodontic treatment is to reduce inflammation in the periapical tissues and promote the tissues’ reparative mechanism to interfere; such as a proliferation of healthy tissue and bone tissue regeneration to aid in recovery. That aim is achieved with non-surgical root canal treatment and sometimes surgical root canal treatment (Friedman *et al.*, 2003, Marquis *et al.*, 2006, Wang *et al.*, 2004).

Historically, endodontic treatment sought to cure the toothache due to inflammation; either of the pulp (pulpitis) or the peri-radicular tissue (apical periodontitis).

In previous centuries the common method used to cure the pain was to cauterize the tissue either with a very hot wire or with chemicals. In 1836 arsenic was introduced and was used to devitalise the pulp. Later on the idea of removing the pulp from the tooth without any toxic chemicals was introduced in the 19th century, which is now described as the procedure of a Pulpotomy (Gunnar Bergenholtz Nov 2009).

Although the primary aim of endodontic treatment is to protect and preserve healthy peri-radicular tissue, it is still not achieved by only removing the pulp tissue. The present treatment concept is more concerned with mechanically and chemically removing and disrupting the bacterial ecosystem, which is the major cause of the infection. This occurs via sufficient biomechanical preparation, which is a mechanical shaping of the canal space to enhance effective chemical cleaning for the whole root canal system (Patel, 2013). The idea behind shaping the canals is to create a tapered funnel shape root canal space, which is wide coronally and narrow apically. The funnel shape aids in the flow and reachability of irrigants inside the root canal system. The aim is to reach everywhere inside the root canal system to the apex. The shaping procedure needs to respect the anatomy of the canals, preserve the tooth structure and maintain the position and structure of the apex. The funnel shape also aids receiving the root canal filling material and achieving a hermetical seal of the root canal space to prevent re-entry and leakage of bacteria (Schilder, 1974).

Shaping of root canal space is a challenging step in root canal treatment, due to the complexity and variability of root canal anatomy (Vertucci, 2005). This is the reason why a lot of research and development in this specific area has been conducted. Research is divided into different aspects some are concerned with the technical side of the treatment, such as studies assessing shaping of the root canal system, different apical size and taper preparation, efficacy of different instruments in preparing the root canal walls and effect of this preparation on the original canal anatomy (Capar *et al.*, 2014c, Card *et al.*, 2002, Gagliardi *et al.*, 2015, Mickel *et al.*, 2007). Some other studies investigated the procedural errors during the preparation and its effect on the technical outcome of root canal treatment (Lin *et al.*, 2005) Other studies investigated the effect of the mechanical shaping with different geometrical parameters on the irrigation used and its reachability inside the root canal system.(Boutsioukis *et al.*, 2010) Obturation of the root canal system is also investigated, assessment of different types of sealers and different techniques of manipulation of the gutta-percha for obturation (Uranga *et al.*, 1999, Wu and Wesselink, 1993). In addition there is research involving the biological aspect of root canal treatment, including investigating the effect of different aspects of shaping the root canal space used in root canal treatment and their effect on the bacteria causing the periapical infection, the effect on the host immunity and how they affect the immune response and the healing capacity (Klevant and Eggink, 1983, Sjögren *et al.*, 1990).

Root canal treatment success or failure has been directly linked to the persistence, recurrence or healing of intra-radicular or extra-radicular infection (ESE, 2006).Unsatisfactory shaping will not allow sufficient chemical cleaning, because multiple areas and spaces are already difficult to reach and only by shaping the canals the irrigant is able to reach these areas and clean them. In addition we might have procedural errors, which can affect the treatment success by failing to reduce bacterial load and remove necrotic pulpal tissues. There are multiple procedural errors, some of them affect the efficacy of the cleaning procedure by compromising the reach of either the instruments or the irrigants to the full dimensions of the canal space and clean them. Other procedural errors affect the structure and our ability to seal the root canal space, resulting in un-successful root canal treatment. However in non-infected root canals, procedural errors may not always influence the success. This is explained by having a non-infected root canal space, which even if not cleaned with high efficacy will still be free of the high bacterial load present in infected root canal system (Lin *et al.*, 2005, Siqueira, 2001).

The primitive features of shaping mentioned by Schilder in 1974 are still utilised today and consists of "continuous taper -largest diameter coronally and narrowest diameter apically, maintenance of the anatomy of the canal and preservation of the natural apical foramen location and size to be as small as practical" (Schilder, 1974). Also there is a different concept of preparation utilised, which aims mainly for large apical size preparation and narrow taper. Some studies showed that larger apical size preparation minimum of ISO #35 decreases the bacterial load apically, as it has been shown by Card *et al* that a high percentage of the infected root canals from mandibular canines, premolars, and molar mesial roots will no longer harbour cultivatable bacteria when instrumented to the sizes used in his study by decreasing the dentine hosting the bacteria in the tubules and also decrease the depth of the tubules in this area allowing the irrigant to penetrate a greater surface area and clean more space (Card *et al.*, 2002). However there are studies which contradict the results that there is no significant difference in the bacterial load between the small and large size apical preparation, as shown by Mickel *et al* that multiple studies have advocated using larger files to clean the apex. Although instrumenting canals to larger sizes may not be prudent in every case, minimal apical preparations based on clinical opinions are far more detrimental to the success of root canal therapy. An appropriate apical sizing method can help the operator avoid unnecessary enlargement of the apex whereas predictably reducing intra-canal debris (Baugh and Wallace, 2005, Mickel *et al.*, 2007).

Initially only stainless steel file systems were available for shaping and they were used as hand files. They had various drawbacks, such as low flexibility and consumed a lot of time and effort to finish the shaping procedure. More recently Nickel-Titanium (NiTi) alloys have been introduced and proven to be better than Stainless steel with their higher flexibility and being more efficient in preparing the canals (Gambill *et al.*, 1996, Garip and Günday, 2001); however they still have some weaknesses and need more development. Nickel-titanium was introduced as either hand file systems or mechanical rotary file systems. The rotary filing system is more efficient and saves time and effort (Glosson *et al.*, 1995). The rotary systems use either a continuous rotatory motion or a reciprocating motion. The recent trends in shaping are to have file systems able to achieve sufficient shaping and cleaning ability in less clinical time, thus reducing clinical costs for equipment and surgery time. This is the reason why single file systems have been introduced, so that shaping procedure from start to finish can be completed with a single file that creates the required apical size, taper and shape of the canal and reduce cost (Bürklein *et al.*, 2012).

Only a limited amount of the root canal walls are instrumented by the endodontic files (Peters *et al.*, 2001a, Peters *et al.*, 2001b). It is still difficult to achieve the three dimensional efficiency, although some preparation is done with wide taper and large size apical preparation. Preparing the canals to a large size coronally and apically, means removing more root dentine which will adversely affect the strength of the roots prepared and make them more liable to vertical fracture (Lertchirakarn *et al.*, 2003). Manufacturers and operators are now looking for files which can achieve the best shaping, cleaning ability and three-dimensional efficiency and at the same time preserve dentine structure, reduce the impact on the tooth strength (Hülsmann *et al.*, 2005a, Peters and Paque, 2010).

With different instruments available in the current market, there are a lot of choices that can be adopted. There are limited evidence available to help chose which file system to use to produce the optimum root canal preparation. On the other hand, we don't know whether the different file systems are going to perform in the same way in different hands with different level of experience, as some the technical outcome may be affected by the skill and experience of the operator undertaking the preparation, such as Dental Students, General Dentists and Endodontists.

It is also not clear which file systems currently available that can be easy to use and handle, either by novice or experienced operators to produce sufficient shaping results in a reasonable time and with none or less procedural errors. Also it is unknown which of the current systems able to achieve the required three-dimensional shaping of root canal system without compromising the tooth structure.

The main theme of the thesis will be about canal shaping and different aspects that can influence this stage of treatment in endodnontics.

Chapter 2: Literature review

2.1 Structure:

A brief overview of the main sections in the literature review highlighting the academic insight and evidence concerning shaping in endodontics:

Introduction: Presenting the aims of root canal therapy & influential factors.

Root canal anatomy: This section presents root canal anatomy and its influence on root canal treatment.

Different techniques for root canal shaping: This section presents different techniques used in root canal shaping and how they developed.

Endodontic instruments: This section presents different endodontic instruments, including hand instruments and nickel titanium instruments.

Methods of assessing root canal instrumentation: This section presents several methodologies mentioned in the literature for assessment of root canal instrumentation.

Effect of operator experience on root canal instrumentation: This section presents the effect of operator experience and skills on the outcome of root canal preparation.

Conclusion.

2.2 Introduction:

Root canal therapy is concerned with treating vital or necrotic dental pulps and its main objective is to decrease the number of microorganisms and debris in the root canal system to prevent or treat inflammation or infection, so patients can retain their teeth for function and aesthetics. Achieving successful treatment is dependent on multiple factors such as; accessing, identifying, negotiating and preparing the canals. However the most important phase in root canal treatment is canal preparation. It is an essential step because it influences the creation of creation sufficient space for delivering antibacterial irrigants and medications to achieve optimum cleaning of the root canal system.

2.3 Root canal anatomy:

The canal preparation is highly affected by variations of root canal anatomy (Nagy *et al.*, 1997, Vertucci, 2005) and in order to overcome these variations, the clinician need to be familiar with root canal morphology and treat every tooth assuming the complex anatomy. Canal anatomy can be challenging and influenced by different factors such as physiologic aging, pathology and occlusion, and the production of secondary and tertiary dentine and cementum (Vertucci, 2005). Secondary dentine is formed throughout the tooth life as a normal process during aging, while the tertiary dentine is formed due to a stimulus from several reasons, such as trauma, caries. Both process of dentine deposition can affect the root canal space and change the location and standard anatomy of the root canal system (Giuliani *et al.*, 2014, Goldberg *et al.*, 2011, Prichard, 2012). This may make the root canal treatment procedure more challenging and difficult to carry out and might result in tooth destruction and iatrogenic damage during the procedure. In addition, abnormal canal orifice configuration makes it difficult to identify the canal location, irregular canal cross section and highly curved canals make it difficult to negotiate and shape, which might result in procedural errors.

Curvature of root canals have been a major factor when assessing the difficulty of root canal treatment; several methods has been introduced for assessing the curvature and deciding on the severity. Most of the methods introduced measure the angles between two imaginary lines drawn on the two-dimensional radiograph of the tooth and by measuring the angle between these two lines the degree of severity of the curvature can be decided (Schneider, 1971). From a clinical aspect, this way of assessment is considered just a guiding tool as it is only a two-dimensional assessment and a lot of the root curvatures are seen in more than one dimension. Another method which was based on three dimensional assessment undertaken with CBCT suggested that the radius of the curvature is more important regarding the difficulty and that the shorter the radius is the more difficult the curve to negotiate and prepare mechanically (Balani *et al.*, 2015, Günday *et al.*, 2005). In addition there are different difficulty assessment tools used to define the category of difficulty of the root canal treatment, such as the American Association of Endodontists (AAE) , the Canadian Academy of Endodontists and Dutch Endodontic Treatment Index (DETI) and the Endodontic Treatment Classification (ETC) forms (Ree *et al.*, 2003). Most of these tools assess the severity of the curvature based on the measurement of the imaginary angle. The more severe the curvature is, the more difficult is to carry out the root canal treatment with a high risk of procedural errors such as asymmetrical dentine removal during preparation; which might lead to ledge formation, canal transportation or perforation.

Those procedural errors could make it difficult to reach the apical third of the canal and eliminate bacteria, as it will prevent the instruments or the irrigation to reach the apical portion of the root canal and achieve the required debridement and cleaning of the root canal space, which is a critical issue. There is a high probability that it will affect the success of endodontic treatment (Sjögren *et al.*, 1990).Some spaces inside the canals are inaccessible mechanically as accessory canals and apical deltas, due to their small structure and the lack of uniformity of their locations inside the canal, that results in them being very difficult to be instrumented mechanically, due to the physical limitations of them (Ida and Gutmann, 1995, Siqueira *et al.*, 1997). The cleaning of these areas is mainly dependent on chemical measures, such as antimicrobial irrigants and medications that are placed between the treatment visits.

2.4 Root canal shaping & different techniques:

Mechanical instrumentation and negotiation of the canals is considered as a practical challenge. The aim of mechanical preparation is to remove pulpal tissue, decrease the bacterial load inside the canal system and to create a sufficient space to allow predictable placement of a canal filling material and achievement of a three dimensional fluid tight seal obturation. Although the preparation of root canals has been described, since early 18th century (Lilley, 1976, Waplington and McRobert, 2014), there was no gold standard preparation sequence of instrumentation proposed until 1961 (Ingle, 1961). Ingle suggested a standardised technique of preparation using a sequence of standardised files and introduced gutta-percha for sealing the resulting root canal space. The outcome of the suggested protocol proved to be successful (Ingle, 1961).

Over time different techniques have been utilised for the canal preparation. The phases of canal space preparation consist mainly of negotiating the canals to full length and then enlarging the apical portion and shaping the rest of the canal to a larger size by successive files, increasing in size and used in shorter lengths (Clem, 1969), this is called step-back technique. This technique did show some drawbacks as; difficulty in canal negotiation and achieving the working length; specially if the original canal diameter is small, also it can cause canal blockage and increases the incidence for preparing the dentine away from the canal space and causes ledging of the canal, which will end up either perforating the root or preventing the instrument reaching the full length of the canal (Weine *et al.*, 1975). Also it leads to dentine debris being extruded through the apex causing post-operative pain and inflammation in the periapical tissues. In spite of the disadvantages of this technique, it proved to be successful in preparing the fine curved canals (Mullaney, 1979) prior to the introduction of Nickel-Titanium instruments.

To help avoid the disadvantages of the step-back technique, an alternative technique was introduced called step down or crown down, which is the complete reverse of the step-back approach. The step-down technique advocates preparation to start from the coronal aspect down to the apical aspect (Morgan and Montgomery, 1984). This technique had several advantages over the step-back technique as; enhancing the penetration of irrigants, avoiding canal blockage and extrusion of debris through the apex, facilitates the determination of working length and help in reducing procedural errors. This technique now is considered widely preferable as a preparation technique irrespective of what type of shaping instrument is used.

2.5 Instrumentation technique:

Utilising the crown down concept, instruments are used in different rotational and reciprocal movements inside the canals. For hand file systems there are different manipulations that can be applied. A Roane balance force technique (Roane *et al.*, 1985), watch winding technique and rotation technique (Cohen and Hargreaves, 2006). The balanced-force is applied by the instruments introduced into the root canal, with a clockwise motion of maximum 180 degrees and apical advancement (placement phase), followed by a counter clockwise rotation of maximum 120 degrees with adequate apical pressure (cutting phase) , the final removal phase is then performed with a clockwise rotation and withdrawal of the file from the root canal (Hülsmann *et al.*, 2005a).This technique minimises the procedural errors especially canal transportation and ledges (Roane *et al.*, 1985).The watch winding movement is a reciprocating movement applied in the range of 30 degrees clock wise and 30 degrees counter clock wise and is used mainly to negotiate the canal and progress to the working length (Cohen and

Hargreaves, 2006). The rotation movement is a quarter clock wise turn and pulling the file to cut dentine and prepare the canals (Cohen and Hargreaves, 2006). For engine driven file systems, continuous rotation or reciprocating movements are utilised, although it is still controversial which type of movement is better, or indeed more efficient. Different studies have been conducted to investigate the difference in efficiency between the two movements of the file systems and their efficacy on canal walls instrumentation, effect on debris extrusion through the apex and incidence of creating cracks in the roots treated (Giuliani *et al.*, 2014, Nevares *et al.*, 2015, Prichard, 2012).

2.6 Endodontic instruments & file systems:

There are a large number of instrument types and designs that has been introduced and developed through history and documented in the literature. In the 18th century only primitive hand instruments which were thin and fine instruments, some excavators and hand cauterizing instruments were available (Lilley, 1976). After that, the first endodontic hand instruments were developed by Edward Maynard (Hülsmann *et al.*, 2005a). In the 19th Century it was recommended that barbed broaches, which are manufactured by cutting sharp, coronally angulated barbs into metal wire blanks should be used for canal shaping and enlargement. In 1885, Gates Glidden burs were introduced for canal preparation, which work well for pre-enlargement of coronal canal areas and achieves a straight light radicular access. K-files were introduced in 1915 and were standardised according to the ISO standardization and specification for endodontic instruments, which was published in 1974. Oltramare first reported the idea of a rotary device, where he used fine needles with rectangular cross sections, which could be mounted to a hand piece (Hülsmann *et al.*, 2005a). The first endodontic hand piece was developed in the 1889 by Williams H. Rollins, where he used specially designed needles in a complete rotation movement. In subsequent years different types of rotary systems where developed by different companies, such as W&H®, Micro Mega® and Kerr®, implementing different motions and ideas. Other ideas were also introduced for canal preparation such as sonic and ultrasonic devices, laser devices and some non-instrumental techniques (Hülsmann *et al.*, 2005a), however until now, file systems either rotary or reciprocating are the most used instruments and considered to be the gold standard in canal preparation (Hülsmann *et al.*, 2005a).

2.6.1 Hand instruments:

The classic approach to canal preparation was by utilising the ISO standardized 0.02 taper stainless steel files used by hand, which generally refers to K-files and Hedstrom files. This means these files have a diameter increase of 0.02 mm per millimetre from the file tip till the length of 16 mm. K-files are manufactured by twisting square or triangular metal blanks and with a non-cutting tip, the cross section of this file have an influence on the flexibility of the file showing the triangular cross section file to be more flexible than the square cross section file(Camps and Pertol, 1994). Also the cross section of the K-files shows why it is used in clockwise and anticlockwise rotations (Hargreaves, 2010). The characteristic of these files causes them to be more rigid and inflexible when they increase in size, which makes them harder to manipulate and less efficient, especially in curved canals because of being more difficult to control the preparation efficiency of them and increase the risk of causing procedural errors as ledging, canal transportation and file separation (Elizabeth M, 2005). Hedstrom files are another type of hand stainless steel file manufactured by milling from round stainless steel blanks (Hülsmann *et al.*, 2005a). Due to their cross section, they are better used in transitional strokes and filing motion and not recommended to be used in rotation movement because of the possibility of instrument fracture, due to being wedged in dentine and not be able to withdraw from inside the canal until unscrewed in reverse to release the dentin chips. These drawbacks have led the manufactures to develop more flexible instruments that can complete canal preparation more efficiently. Similar techniques were used to manufacture files of greater flexibility made of NiTi alloys, which have been very useful in preparing highly curved canals.

2.6.2 Nickel titanium instruments:

2.6.2.1 Nickel titanium alloy:

Nickel titanium alloy was developed by Buehler, a metallurgist who was investigating the development of a non-magnetic, salt resisting and water proof alloy for the space program at the Naval Ordnance laboratory in silver springs, Maryland, USA (Buehler *et al.*, 1963). The chemical and physical properties of this alloy were found by Beuhler to be capable of producing something called a shape memory effect when controlled heat treatment was applied (Buehler *et al.*, 1963). The alloy was called Nitinol in relation to the elements that it is composed of Ni for nickel, Ti for the titanium and NOL from the Naval Ordnance laboratory. The NiTi alloy was found to have super elasticity and shape memory properties. The alloy was shown to have high strength and a lower modulus of elasticity compared with the stainless steel alloy (Andreasen and Morrow, 1978). The advantages of the alloy encouraged the idea of using it for root canal instruments during the preparation of curved canals, utilising the low modulus of elasticity and lower risk of permanent deformation of the file compared to the other alloys (Schäfer, 1997, Thompson, 2000).

Since the early 1990s, several instrument systems manufactured from nickel-titanium (NiTi) alloys have been introduced into the endodontic market and have dramatically influenced the preparation techniques and have gained wide popularity amongst clinicians. The nickel titanium alloys used in manufacturing the root canal treatment instruments contain approximately nickel 56 weight % and titanium 44 weight %. The NiTi alloy can be present in different crystallographic forms based on stress and temperature applied, as shown in Figure 2.

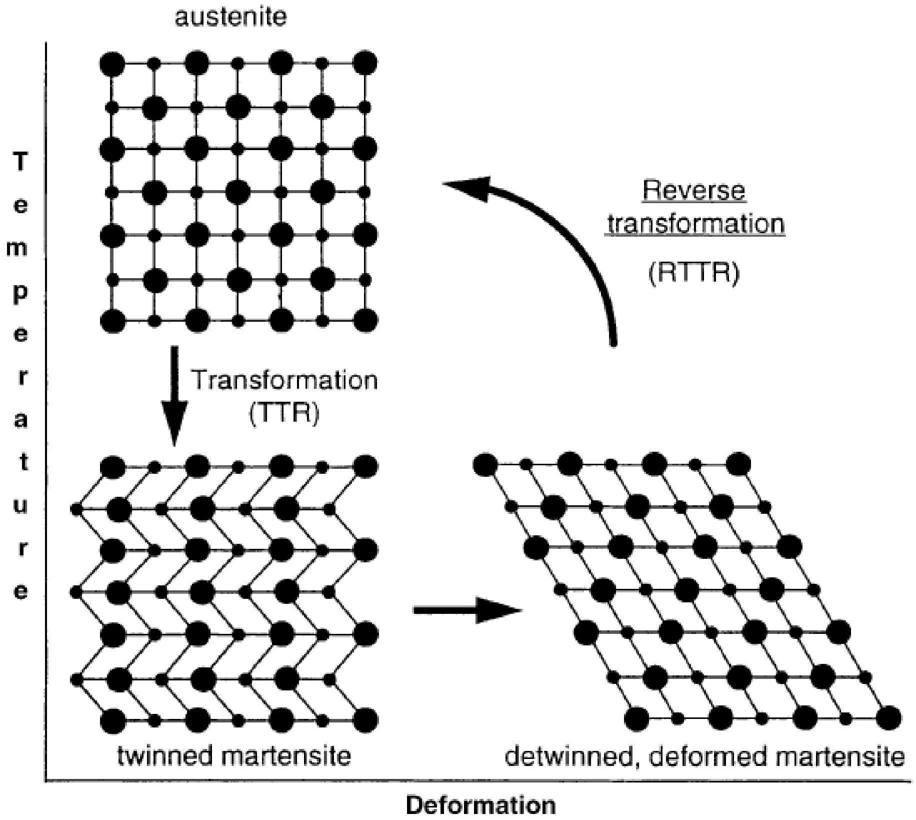


Figure 2: Illustration of the transformation of the NiTi alloy between different crystallographic forms (Thompson, 2000).

The Thermodynamic properties of NiTi alloy allows the instruments to be manufactured with enhanced properties, such as higher flexibility and shape memory compared with stainless steel files. The two different phases of relevance in clinical dentistry and the reason for these properties are the austenite and martensite phases, shown in Figure 2 and 3.

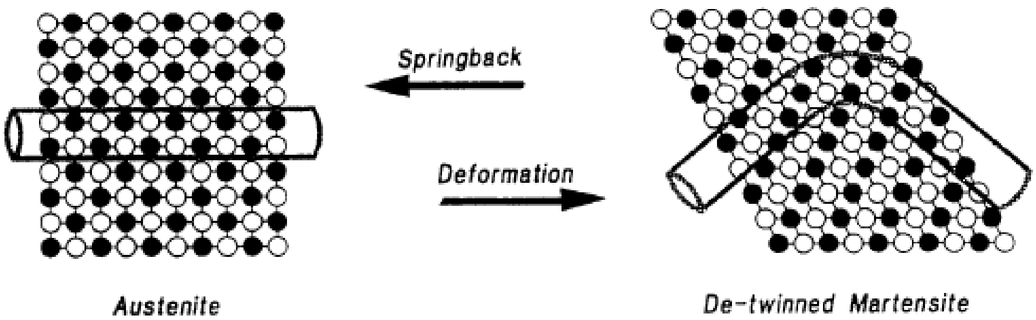


Figure 3: Illustration of super- elasticity of NiTi alloy (Thompson, 2000).

The Nickel titanium alloy is present in a stable body- centred cubic lattice, which is referred to as austenite phase, or parent phase shown in Figure 2, and that phase is usually seen at high temperature ranges 100 degrees Celsius. The alloy tends to change its crystal structure and physical properties when it is cooled, over a transformation temperature range. The modulus of elasticity and the yield strength tend to be affected significantly by the change in temperature. The transformation is called martensitic phase or daughter phase and that what induces the controlled memory effect in NiTi alloys (Thompson, 2000). The martensitic phase is more ductile and liable to deformation compared to the austenite phase. The deformation can be reversed be heating the alloy back above a specific temperature, called (reverse transformation temperature range) and with that, the alloy reverts back to the austenite phase (Parent phase) with the crystal structure, previous shape and physical properties. This phenomenon is described as the shape memory effect shown in Figure 4.

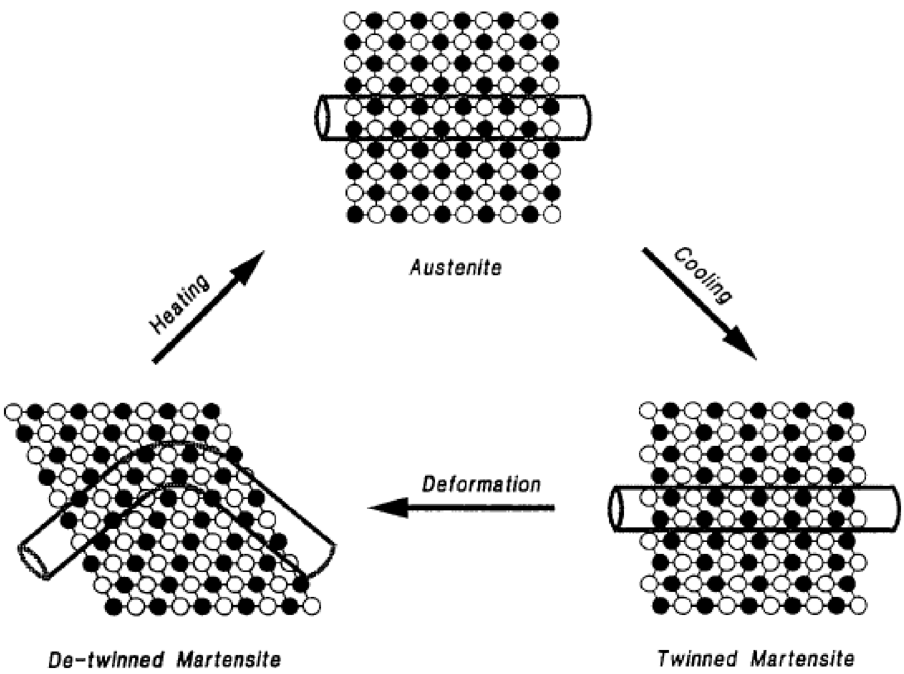


Figure 4: Illustration of the shape memory effect of NiTi alloy

The other form of transformation between the allow phases is a stress induced transformation to the martensitic phase. The transformation occurs as a result of application of stress to the alloy, such as the stress induced during preparation of root canals. In most metals, applying an external force can cause a plastic or a permanent deformation, while in NiTi alloys it induces a martensitic transformation. The stress/strain behaviour of NiTi alloys has a range of plastic deformation, which the alloy can undergo and will still be recoverable to the initial phase. This range of plastic deformation with NiTi is much higher compared to conventional metal, where the elastic deformation is recoverable in a small percentage however when a plastic deformation occurs it is unrecoverable (the deformation is permanent) as shown in the stress/ strain curve present in Figure 5. The nickel-titanium alloy allows deformation of up to 8 % strain to be fully recovered compared to less than 1 % in other alloys, such as stainless steel in relevance to the endodontic instruments (Andreasen and Morrow, 1978, Thompson, 2000). In addition, there is a phase in NiTi alloy called R-phase, which can be temperature induced and stress induced. It is considered a special type of the martensitic transformation, which is seen just after the elastic deformation of the austenite phase and that phase extends until the start of the stress induced martensitic phase as shown in Figure 5. The R-phase is martensitic in nature, but not the martensite responsible for the shape memory and super elasticity effect, however it still has some of these properties but in a very minimal effect and narrow temperature range. The R-phase to austenite transformation is reversible and happens at a low temperature range between 20 and 40 degrees C and with minimal stress (Zhou *et al.*, 2013). The R-phase has a lower modulus of elasticity compared to the austenite phase, but it exhibits higher fatigue/fracture resistance and with some heat treatment can have high flexibility and strength (Zhou *et al.*, 2013).

The relationship between the metallurgical properties and the mechanical properties of the NiTi endodontic instruments, should be understood by clinicians; as it has a significant impact on the performance of the NiTi instrument. Being aware of how these instruments behave will influence the protocol of using them and help in achieving the best efficiency with them.

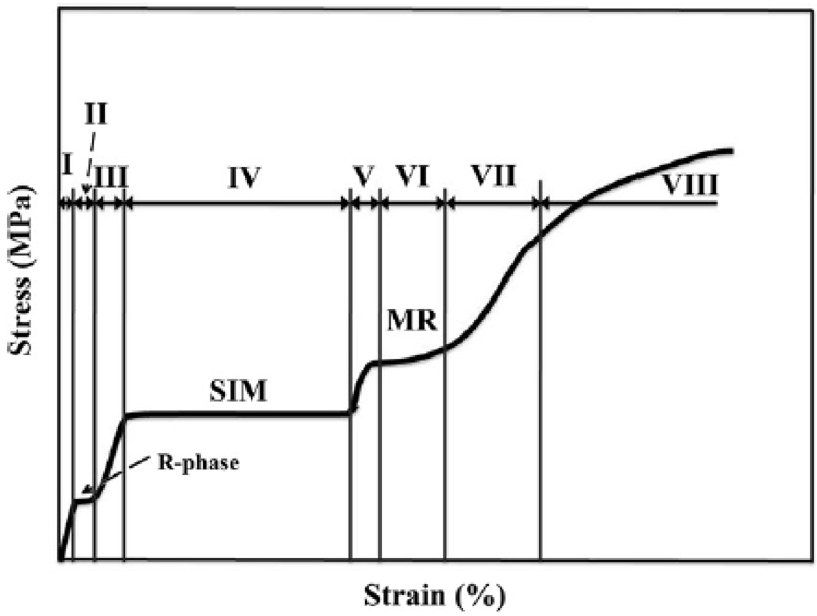


Figure 5: Schematic drawing of tensile stress-strain curve of equiatomic NiTi alloy. It shows eight distinct stages: I, elastic deformation stage of austenite; II, stress plateau related to the transformation from austenite to R-phase; III, elastic deformation stage of R-phase induced by stress (stress-induced martensite, SIM); IV, stress plateau related to the transformation from R-phase to martensite caused by SIM; V, elastic deformation stage of martensite; VI, martensite reorientation (MR) stage; VII, uniform non-linear deformation stage of reoriented martensite; VIII, plastic deformation stage of reoriented martensite (Zhou et al., 2013)

2.6.2.2 *Manufacturing of NiTi Instruments:*

Most of the NiTi instruments are manufactured by a grinding or milling process or plastic deformation under heat treatment, because they cannot be manufactured with twisting in the same way as the stainless steel files, due to the high flexibility of the alloy. In addition, they have surface treatment to improve their surface quality, due to the irregularities left by the milling process that can affect the cutting efficiency of the instruments (Rapisarda *et al.*, 2000). Examples of these surface treatments are electro polishing and coating with titanium nitride. The NiTi instruments are still liable to corrosion in some cases, which affects their physical properties.

More developments have been seen with the NiTi alloys and the martensitic phase of the alloy. A new alloy was introduced in 2007 to the dental market by DENTSPLY called M-wire (DENTSPLY, 2007), the M-wire is an alloy formed by thermomechanical processing procedure to the NiTi alloy. The M-wire has got some martensitic phase in its microstructure which improves the mechanical properties (Alapati *et al.*, 2009) .That allows the instruments to be manufactured from smaller core diameter adding to the flexibility of the instrument and still demonstrate strength and great resistance to cyclic fatigue. There are different brands of these file systems, such as ProFile GTSeries X, ProFileVortex, and ProFileVortex Blue (*Dentsply Tulsa Dental Specialties, Tulsa, OK, USA*), controlled memory (CM) files (e.g. HyFlex CM*: Coltene Whaledent*). Other developments were introducing the R-phase to the endodontic instrument market and manufacturing the instruments utilising this phase of the NiTi alloy, such as Twisted files (TF) and K3XF files (*SybronEndo,Orange, CA*). They have shown improved flexibility and cyclic fatigue resistance compared to the traditional NiTi endodontic instruments. Some modifications has been done to the NiTi alloys to be thermally (heat) treated, to produce files having different alloy microstructure and undergoes phase transformation with different temperatures such as, the Wave One gold (*Dentsply Maillefer, Switzerland*), Reciproc Blue (*VDW GmbH, Munich, Germany*), and XP-endo Shaper (*FKG*

Dentaire SA, La Chaux-de-Fonds, Switzerland). The heat treated alloys combine the properties of both phases of NiTi alloy to try and utilise the benefits of each phase. Another major advantage of the NiTi files is the ability to make them with large taper and apply different and progressive tapers on the same file without affecting their flexibility and being less rigid in larger sizes compared to their stainless steel counterparts. Tapers can range from 0.04 to 0.012, however the specific design specifications can vary such as; tip size, taper, cross-section, helix angles, pitch and either landed or non-landed files. However the undesirable and unexpected separation of the instruments caused by cyclic fatigue and/or torsional overload still remains of a serious concern and drawback during clinical use (Zhou *et al.*, 2013).

When considering all the properties of NiTi alloy, the three properties that are of main interest in endodontics, are super-elasticity, torsional fatigue resistance and high resistance to cyclic fatigue, which are fundamental requirements of endodontic instruments for successful use. These three properties allow the instruments to be used in continuous rotation movement in highly curved canals; respecting the canal anatomy and without the high risk of instrument separation. NiTi files have dramatically improved canal preparation and reduced the incidence of several procedural problems such as; file breakage, blocks, ledges and perforations (Hülsmann *et al.*, 2005a). However, they still have some limitations: especially the rotary files, such as the inability to explore the canal system (scouting) and the fact that a glide path still needs to be created with a small size flexible hand file, although there are recent files introduced to the market, which claim to be capable of creating a glide path without the need of hand files, such as Proglider file made by (*Dentsply millfeller, Switzerland*) and the scout race and ISO 10 race files made by FKG. There are also some prerequisites such as, achieving adequate access cavity design, straight line access, and frequent irrigation during instrumentation to avoid the procedural errors especially with rotary NiTi files (Hülsmann *et al.*, 2005b, Patel and Rhodes, 2007) .

2.6.2.3 Design of NiTi instruments:

There are numerous endodontic instruments present in the dental market with different design features and properties. The NiTi endodontic instruments have undergone five different generations of development, with certain changes in the file design and alloy used for manufacturing (Haapasalo and Shen, 2013). The main components that change in the design between instruments are; cross section of the file, the tip of the instrument, the taper on the instrument, the flute design and the cutting edge and radial land of the instrument. The cross section of the file affects the diameter of the file, the strength and flexibility of the file, the way the file contacts the walls of the canals, how much it cuts and how much stress it induces on the canal walls during cutting dentine.

The tip of the file is a working part, which performs the guiding action of the instrument. There are two types of the tip: an active tip, which has sharp configuration and cutting edges, or a passive tip with has a rounded configuration and non-cutting edges. The instruments with active tips are made for removal of dentine or obturation materials from the root canal. One of the main disadvantages of the NiTi instruments is that they lack tactile feedback; Because of this, the instrument with an active tip requires caution in use, as there is a high risk of ledging or perforating the root canal if the instrument gets deviated from the canal axis. The majority of the NiTi root canal instruments have passive tips, especially the recently designed ones (Peters, 2004).

All the root canal instruments have a degree of taper along their working surface. Some of them have progressive taper and some of them have constant taper and some have variable taper. It all depends on the concept behind the file system design. Some are designed to prepare the canals in a certain sequence and in different places inside the canal, so they will have different percentage of taper along the file working surface and different between the files in the preparation sequence. It has been reported that files with progressive taper shape the canal more quickly compared to the ones with constant taper (Bergmans *et al.*, 2003). The other majorly important aspect of design is the instrument flute. The flute is a set of grooves forming the surface configuration of the instrument, which resulted from manufacturing process of the NiTi blank and affects the cutting ability of the instrument. The adjoining flutes form the cutting blade of the instrument. The flutes are characterised by different parameters, which are the helical angle, pitch and configuration of the fluting (Rake angle). The helical angle is the angle formed between the blade and the long axis of the instrument; the variability of the helical angles is an important factor to aid in moving the debris up out of the canal. A constant or similar helical angle makes the instrument more prone to debris accumulation, which will lead to a higher torque on the instrument and leads to potential separation (Haapasalo and Shen, 2013). The pitch of the flutes is the distance between the two points on the correspondent leading edge of the working surface of the file. The pitch has an effect on the screwing effect or the dragging and pulling of the instrument inside the canal. A constant pitch will cause more dragging and pulling inside the canal and the variability in the pitch will decrease the screwing effect dramatically (Haapasalo and Shen, 2013). Also with the smaller pitch the instrument will have more resistance and less cutting efficiency (Haapasalo and Shen, 2013). The surface configuration or the rake angle of the working surface of the instrument is the angle formed by the leading edge of the instrument and the surface to be cut. The rake angle can be positive, negative or neutral. If the angle formed between the edge and the surface to be cut is acute then the rake angles is said to be negative. If the angle formed is obtuse then the rake angle is called positive angle. The cutting efficiency of the instrument is also dependent on the rake angle of the cutting edges. The dentine needs a sharp instrument because of its resiliency, in another words an instrument with positive rake angle. However most of the endodontic instruments are of a negative rake angle or neutral angle, which results in scraping action rather than cutting action and requires more energy to achieve the required cutting (Haapasalo and Shen, 2013). The ideal instrument will have a slightly positive rake angle, and not an overly positive one, to avoid threading. Another design aspect that affects the cutting efficiency of the instrument is the radial land. The radial land is the flat area that falls directly behind the cutting edge of the instrument. The radial land touches the canal walls at the periphery of the file and limits the depth of the cutting and reduces the tendency of the file to screw into the canal and reduce the progression of micro cracks and transportation of the canal. The less wide the radial land is; or the lack of it allows the instrument to be sharper and more efficient and also the design of the instrument will have a reduced volume of metal and this allows it to be more flexible. The radial land also increases the resistance of the file during rotation, resulting in increased torque and that my increase the risk of instrument fracture (Koch, 2002).

2.6.2.4 Mode of Failure of NiTi instruments:

There is still a major concern with the NiTi instruments and their tendency to fracture. Due to the high flexibility and the shape memory effect, the signs of the instrument deterioration is not easily recognised in the NiTi instruments without magnification, compared to the stainless steel instruments which can often be seen to be undergoing deformation. The NiTi instruments have two main modes of failure or fracture, the torsional failure and the flexural fatigue failure (McGuigan *et al.*, 2013). Torsional failure occurs when the instrument, generally the tip as it is the weakest point, becomes locked in the canal while the shank of the file is still rotating. Once the elastic limit of the instrument is exceeded the instrument fractures instantly. Most of these instruments show signs of plastic deformation such as, twisting or unwinding (McGuigan *et al.*, 2013). The other mode of failure is the flexural fatigue, which can happen when the instrument rotates continuously in a curved canal undergoing tension and compression cycles. When the point of maximum flexure of the instrument is reached that eventually results in fracture. Flexural fatigue usually occurs due to the overuse of the alloy and also due to other factors that contribute to the metal fatigue, such as corrosion and thermal changes as expansion and contraction (Andreasen and Morrow, 1978). Some countries, including the UK have rules and regulations for using the endodontic files as a single use instrument, in concerns about decontamination in relation to prion based disease, but that results as well in avoiding the overuse of the instrument and failures resulting from this (McGuigan *et al.*, 2013). However, the literature is still controversial about which mode of failure is dominant and some instrument failures are due to a number of modes of failure and some are due to other factors, such as the operator experience and the protocol or technique for using the instrument (McGuigan *et al.*, 2013).

2.6.2.5 Developments in NiTi instruments*:*

As many rotary systems required several files to complete the canal preparation and with the concerns over file breakage, sterilisation and cost efficiency, this influenced the thoughts of manufactures to try to reduce the number of instruments necessary to achieve ideal preparation. Some manufacture's succeeded in decreasing the number of files and some went to a single instrument concept. Lately the use of NiTi files in reciprocating motion in addition to the single instrument concept was introduced. This allowed the canal preparation to be completed using a single file. This concept was first reported by Yared (Yared, 2008), then in 2011 Wave-one and Reciproc files where introduced by Dentsply and VDW based on what Yared observed. Both systems are manufactured from the modified NiTi alloy the M-wire. A new addition to the reciprocation motion was also introduced called multiple reciprocation motion. The reciprocating movements occurs in an anti-clock wise motion suggested to be 130 degrees followed by releasing clock-wise motion in 50 degree ,which means the instrument need 3 rotations to complete 360 degree rotation thus the elastic limit of the instrument is not exceeded (Prichard, 2012). Advantages of these systems are reducing the potential of instrument breakage, reduce the risk of cross contamination and they are cost efficient as well. The Reciproc file is even recommended to be used without the need to create a glide path before its introduction into the canal (De-Deus *et al.*, 2013), but this is preferred in straight and reasonable sized canals .

Other very recent development to the NiTi file systems is the introduction of the controlled memory files and the thermally treated alloys. The Hyflex CM file was the first, introduced by *Coltène Whaledent* for controlled memory alloys. The Wave one and ProTaper Gold produced by Dentsply and the Reciproc blue produced by *VDW* are the first in the thermally treated alloys file systems. All these recent files can be pre- bent or pre curved and they have higher flexibility and increased fracture resistance (De-Deus *et al.*, 2017, Plotino *et al.*, 2017).

Although all these recent developments have been implemented, mechanical preparation is still not achieving the optimum results and some of the surface area of the canals is not touched or instrumented by the files. The literature quotes 35 – 55 % of root canal systems not instrumented with the incidence being higher in oval and c-shaped canals (Peters *et al.*, 2001b). Thoughts now are going towards developing new files called anatomic shapers and finisher files which are designed to overcome this issue and instrument the surface area of the canals more efficiently achieving the three-dimensional instrumentation. It is postulated that they help in reaching inaccessible areas and removal of the debris, an example of these files is the XP-endo Shaper (XPS) (*FKG Dentaire SA, La Chaux-de-Fonds, Switzerland*), which is introduced recently and mainly used as a single file for shaping the canals and try to achieve a better three dimensional efficacy. The XP-endo shaper is made of thermally treated alloy called MaxWire® and the concept behind it is being very flexible to expand beyond its core to prepare and adapt to the root canal space anatomy. The XP-endo Finisher (XPF), which is used as a finishing file after completing the preparation to help in debris removal and biofilm disruption. It is based on the same concept of expansion beyond the file core, but in different pattern compared to the XPS. There are very few studies present in the literature regarding both files. The XP-endo Finisher was shown to help in removal of calcium hydroxide dressing from inside the canals with similar effect to ultrasonic irrigation, and also showed to have a positive effect on the debris and smear layer removal from the canals (Elnaghy *et al.*, 2017, Wigler *et al.*, 2017). Only one study mentioned the effect of XPF as an irrigant agitator on the biofilm in the apical portion of the root canal. The XPF shown to help in removal of the biofilm in hard to reach areas in the root canal system compared with the ultrasonic (Bao *et al.*, 2017). Regarding the XP-endo shaper, the number of studies is even lower than the XPF. One study showed the effect of the file on causing on dentinal micro-cracks during preparation and the XPS showed that it does not induce any dentinal cracks (Bayram *et al.*, 2017). The other 2 studies one of them investigated the torsional resistance of the file and showed that it have a low torsional resistance compared to other file systems such as, TRUShape (TRS; size 30, .06 taper, *Dentsply Tulsa Dental Specialties, Tulsa, OK, USA*), ProFile Vortex (PV; size 30, .04 taper, *Dentsply Tulsa Dental Specialties*) and FlexMaster (FM; size 30, .04 taper, *VDW GmbH, Munich, Germany*) (Elnaghy and Elsaka, 2017). The second one is the most recent one investigated the shaping abilities of the XPS in oval shaped canals compared with Vortex blue (*Dentsply Tulsa Dental Specialties, Tulsa, OK*) utilising micro-computed tomographic imaging for analysis and the XPS showed that it can prepare better and touch more canal walls compared to the Vortex blue in oval shaped canals (Azim *et al.*, 2017).

Considering the limited number of the studies present and the majority being *in vitro* and in simulated models, more studies and investigation regarding these two files is going to reveal more information and facts about the efficacy and abilities of these files.

2.7 Different Methods of assessing Instrumentation:

The literature is full of studies on different aspects of instruments performance and efficiency in terms of; cleaning ability of the instruments, shaping ability of the instruments and properties of the instruments. Several methodologies have been described to analyse and evaluate the performance of the root canal instruments (Barthel *et al.*, 1999, Dummer *et al.*, 1991, Habib *et al.*, 2015).When analysing the quality of root canal preparation created by the instruments and different techniques, different parameters should be considered such as the cleaning ability and shaping ability of these instruments. Studies done are mainly *in vitro*, either on human extracted teeth or simulated canals in form of resin blocks or anatomic plastic teeth (Habib *et al.*, 2015). The majority of these studies (90 %) or more used extracted teeth, while the rest of studies used simulated root canals in resin blocks (Habib *et al.*, 2015). The major advantage of using extracted human teeth is they resemble the closest scenario to the clinical situation; however it is difficult to collect, disinfect and standardise them in terms of canal length and width, curvatures, dentine hardness and calcification (Hülsmann *et al.*, 2005a). On the other hand, simulated canals in resin blocks allow standardisation of length and width, curvature and surface hardness. The standardisation made assessment easier to apply and guarantees high degree of reproducibility of the experimental design, which makes the results of such studies valid and transferable to human teeth (Lim and Webber, 1985b). Nevertheless, there are still some concerns about the resin simulated canals regarding the difference in hardness between the dentine and resin. Micro-hardness of dentine was found to be more than the resin and for removal of natural dentine, nearly double the force is applied that is needed for the resin (Lim and Webber, 1985b). Also the size of the resin chips compared to the natural dentine chips may not be the same, which results in more blockage liability and difficulty to remove debris in resin canals (Lim and Webber, 1985b).

Methods used to evaluate the efficiency of root canal instrumentation related to the cleaning ability are different from the ones used to evaluate the shaping ability. Concerning the cleaning ability, the evaluation is based on the volume of debris and the un-instrumented root canal walls. The assessment was carried out in many studies either by histological sections of the human root canals (De-Deus and Garcia-Filho, 2009, Walton, 1976) or scanning electron microscope (SEM) (Prati *et al.*, 2004). In addition the high-resolution Micro-computed tomography (Micro CT) was used to evaluate the instrumented surfaces of the canal walls (Peters *et al.*, 2001a, Peters *et al.*, 2001b). The histological sections include obtainment of serial cross sections and assessment of the remaining tissues using morphometric analysis. The SEM examination, evaluates different parameters such as smear layer, debris and surface profile. Some of these methodologies have negative aspects, such as for the histological analysis it is considered a destructive method and difficult to standardise and apply. The SEM evaluation provides us with a lot of details and information about the surface topography and composition, but is still expensive equipment which is difficult to obtain and use. The Micro-CT is considered a non-invasive technique, because it depends mainly on imaging of the extracted teeth or the simulated canals in blocks or anatomic plastic teeth without the need of obtaining histological samples or sectioning the teeth. However it is relatively slow and needs experience to handle and use.

The Micro computed tomography studies have shown that even with the most developed instruments, there are still some areas of root canal systems that cannot be reached, instrumented or cleaned mechanically, taking into consideration the variability of the root canal space anatomy (Peters *et al.*, 2001a, Peters *et al.*, 2001b).

Other methodologies have been mentioned to assess the shaping ability and changes that happens inside the canals after preparation. These include silicon impressions (Barthel *et al.*, 1999), super imposing of radiographs before and after shaping and comparative analysis done utilising computer aids (Mikrogeorgis *et al.*, 2006).

In Addition the Muffle system which was developed by Bramante et al. to evaluate changes in canal diameter (Bramante *et al.*, 1987). Another method of evaluation for the simulated resin canals is also to view them under high magnification to check for procedural errors or to take pictures for the blocks before and after preparation and do a visual comparative analysis. For extracted teeth, clearing is also one of the methods to evaluate changes inside the canals before and after instrumentation with the aid of magnification (Robertson and Leeb, 1982). The most developed technique for evaluation of canal changes and for acquiring geometrical changes is three dimensional imaging by computed tomography, which can be done either by Micro-CT (μCT) or Cone beam CT (CBCT). Nielsen *et al*. found that Micro-CT is capable of producing the internal and external morphology or root canal anatomy without being destructive and can also demonstrate the changes before and after preparation and used in comparative analysis (Nielsen *et al.*, 1995).

Lately most of the investigators have been more interested and concerned with micro-computed tomography (Micro-CT, CBCT) and that is mainly because normal 2-D radiographs cannot reflect all the changes in the anatomical features and geometrical dimensions. However, most of studies are applied *in vitro*, because CBCT scans are of higher radiation dose compared to normal radiographs; which can affect the patients negatively and the μCT is a lab based device not designed for human use. Also both machines are still expensive and complex devices to use (Okano *et al.*, 2009).

2.8 Effect of operator experience on root canal instrumentation:

There is a whole different side to the story of instrumentation and preparation efficiency, which is the experience and skills of the operator using the instruments and will it affect the outcome of root canal preparation. The outcome of root canal preparation and the efficiency of instrumentation are dependent on multiple factors, however operator experience is considered one of the major factors (Baumann and Roth, 1999).

Different studies in the literature showed the influence of different levels of experience on the outcome of root canal preparation, Such as preparation efficiency, preparation time and influence on instrument breakage (Baumann and Roth, 1999, Mandel *et al.*, 1999, Mesgouez *et al.*, 2003). Most of these studies are undertaken on resin simulated canals. Resin simulated canals are not the best way to resemble the clinical situation, however it allows us to standardise different variables such as canal length, width, cross section and degree of curvature. Standardisation will allow the results to be more accurately linked to the operator experience, rather than affected by other different variables. Studies described that, operators with high level of experience produce better outcomes in terms of preparation efficiency, preparation time and they tend not to get a lot of instrument breakage (Mandel *et al.*, 1999, Mesgouez *et al.*, 2003). It is not just related to operators with high level of experience as endodontists, the outcomes are even different when comparing undergraduate students with very minimal or no experience in root canal preparation to general dentists with little experience. However in some studies operators with little experience showed better technical outcomes of root canal preparation (Baumann and Roth, 1999).

2.9 Conclusion:

In conclusion, it is recommended to use recent technologies as computed tomography in investigations and studies done, considering the advantages it provides over the other techniques (Habib *et al.*, 2015). This gives the chance to be able to analyse the performance of the instruments introduced more accurately and to help in developing a new instrument capable of achieving better cleaning and shaping ability in root canal system.

A main concern at the present is to find a Nickel-titanium rotary file system, which can be used safely and efficiently by operators of little or no experience and produce satisfactory outcomes in terms of less procedural errors, efficient time of preparation. Also to investigate the possibility of developing a new file system capable of instrumenting the root canal space in three dimensions and with high efficacy and interrogate the abilities of the recently introduced systems in the market. The other concern is to investigate the capabilities of the recently introduced file systems to the market and to verify if they can achieve better instrumentation in a three dimensional manner and with higher efficacy. In addition to these is to explore the possibility of developing novel file systems capable of achieving the optimum instrumentation efficacy.

Chapter 3: An investigation of technical outcome & procedural errors produced by novice operators with ProTaper Universal and ProTaper Next nickel titanium instruments in simulated root canals.

3.1 Introduction:

The shaping of a root canal system can be the most challenging and complex phase of root canal treatment, due to the complexity and variation of root canal anatomy (Vertucci, 2005). Root canal treatment success or failure (the outcome of endodontic treatment) has been directly linked to sufficient mechanical and chemical debridement of the root canal system. Iatrogenic alterations to the original canal shape, which we define as procedural errors, will affect the debridement process and will affect the treatment outcome, especially in infected root canals (Lin *et al.*, 2005). Although the presence of a procedural error still affects the debridement process in a non-infected root canal, it does not have as much influence on the treatment success, due to the absence of bacteria and bacterial toxins (bacterial biofilm) inside the root canal system (Lin *et al.*, 2005). Shaping of root canals was historically undertaken using stainless steel hand files. Now, technology has helped in providing more flexible and motor driven NiTi files. These files help decrease the risk of procedural errors occurring during root canal shaping, however, the operator still needs a reasonable amount of experience to achieve the best outcome. Inexperienced operators as undergraduate students may produce many procedural errors when shaping root canals using NiTi files; this could discourage some of them from performing root canal treatment and/or reduce their confidence (Eleftheriadis and Lambrianidis, 2005, Khabbaz *et al.*, 2010). This confirms the need for extensive hands-on pre-clinical training before treatment is carried out on patients for the first time.

Although there is no standardised protocol for the pre-clinical teaching , it is common practice to use a combination of plastic root canal models whether they are simulated teeth or resin blocks and extracted human teeth for these exercises *(Dummer, 1991)*.Simulated canals in resin blocks or plastic teeth are more preferred, because they are standardised, easy to find and reduce the inconvenience (technical demands and time) of disinfecting extracted human teeth. Also acquiring human extracted teeth can be a potential problem, due to the numbers required and because of the restrictions of the Human Tissue Act and the need for patients consent to approve the use of them for teaching or research purposes. Training undergraduate dental students in the use of the most up to date and innovative file systems used in endodontic preparation, that are safe and easy to use, is a desirable aim. This will reflect on their clinical skills and confidence in managing patients that need root canal treatment in the future and should result in better quality root canal treatment outcomes. Considering the recent updates in endodontic rotary file systems, a relatively new system has been introduced “ProTaper Next” (DENTSPLY) shown on Figure 6.

Figure 6: ProTaper Next NiTi rotary file.

ProTaper Next (PTN) is a fifth generation NiTi instrument and been described to produce better technical outcomes (DHINGRA *et al.*, 2014, Gagliardi *et al.*, 2015), in addition to saving time and costs because of the need for fewer files during the preparation sequence. One of the major developments made to the ProTaper Next files over the ProTaper Universal (PTU) in terms of design and properties, is that the file is manufactured from a specific phase of Nickel-titanium alloy called the M-wire. M-wire increases the flexibility of the file and improves the resistance to cyclic fatigue. That results in decrease in the potential for separated instruments, which indicates a greater margin of safety compared with ProTaper Universal (Pérez-Higueras *et al.*, 2014).The manufacturer has applied an off centred cross section and the progressive taper concept on the file ,which decreases the screwing effect of the file, prevents over instrumentation , creates more space for debris to escape and decreases the risk of instrument getting high resistance inside the canal and separating due to torsional fatigue. It has been shown that the ProTaper Next produces fewer cracks in dentine than ProTaper Universal and extrudes less debris during canal preparation (Capar *et al.*, 2014a, Capar *et al.*, 2014b). The Pro-Taper Next file system produce a unique asymmetrical rotary motion at any given cross-section (swaggering effect) (Ruddle *et al.*, 2013). It offers more space for enhanced cutting, loading and removing debris, which means a smaller size file cuts more efficiently compared to a large stiffer file as shown in Figure 7.

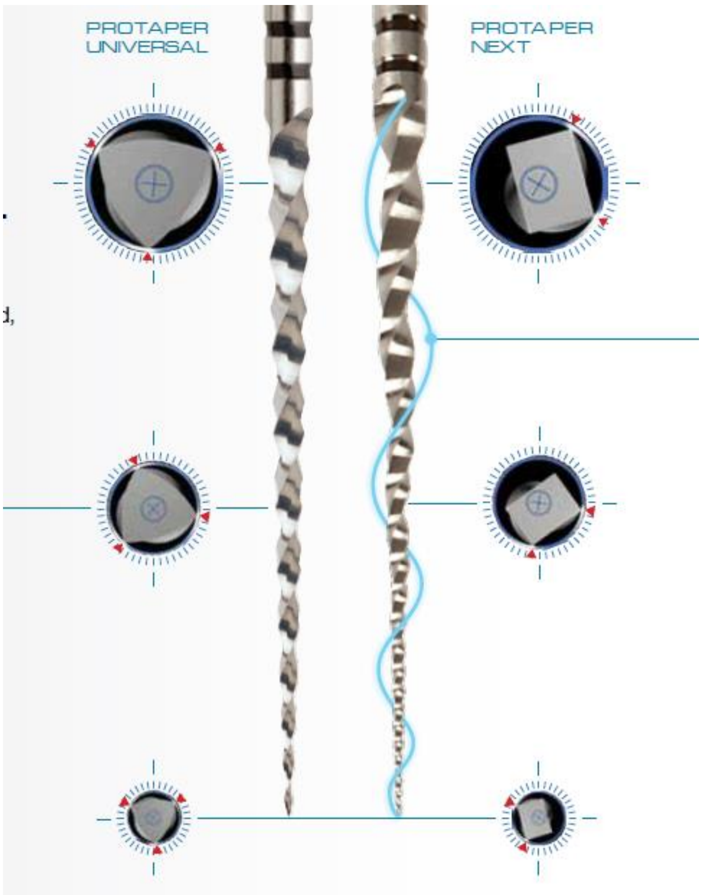


Figure 7:Cross-section of PTU & PTN showing how they contact the canal walls and space present around them for debris removal.

The area of investigating preparations done or the outcome achieved with these new rotary NiTi files in hand of novices has not yet been well established in the literature, therefore the aim of this study was to compare the outcome of ProTaper Next against ProTaper Universal in the hands of novice operators, in relation to the frequency of procedural errors and the time taken for preparation.

3.2 Null hypothesis:

There is no difference in the incidence of procedural errors during simulated root canal preparations and the time taken during the preparation using ProTaper Universal and ProTaper Next.

3.3 Methodology:

This study is an *in vitro* crossover randomised controlled double blinded trial, completed by 66 fourth -year dental undergraduates at the University of Liverpool Dental School. All the students were “blinded” to avoid the bias in their performance and preference. The undergraduates have already completed a preclinical course in basic endodontics during their third year. Their previous training encompassed training with hand preparation techniques only; using stainless steel K-files and Pro-taper Universal Hand instruments.

The students were split into two groups, group A of 36 students and group B of 30 students in order to optimise space and staff student ratios within the phantom head facility at Liverpool. The students were assigned randomly to the two different groups using their seat numbers; both groups had the same teaching on their individual sessions.

All students were taught the use of both Pro-taper Universal Rotary files (*Dentsply Maillefer, Ballaigues, Switzerland*) and Pro-taper Next rotary files (*Dentsply Maillefer,Switzerland*) according to manufacturers' instructions. This was followed by a live demonstration of each system before the undergraduates' commenced preparation on simulated root canal standardised blocks 16 mm in length (*Dentsply Maillefer, Ballaigues, Switzerland*).

I. Pro-taper Universal Rotary using S1, S2, F1 and finishing with F2 file with 0.25mm tip and 8% taper.

II. Pro-taper Next Rotary using X1 and finishing with X2 file with 0.25mm tip and 6% taper

The students used X-Smart motors (DENTSPLY) using pre-programmed settings for each file system according to the manufacturer's instructions.

Each student completed preparation of two simulated resin blocks using the two file systems in a crossover design shown in Figure 8.

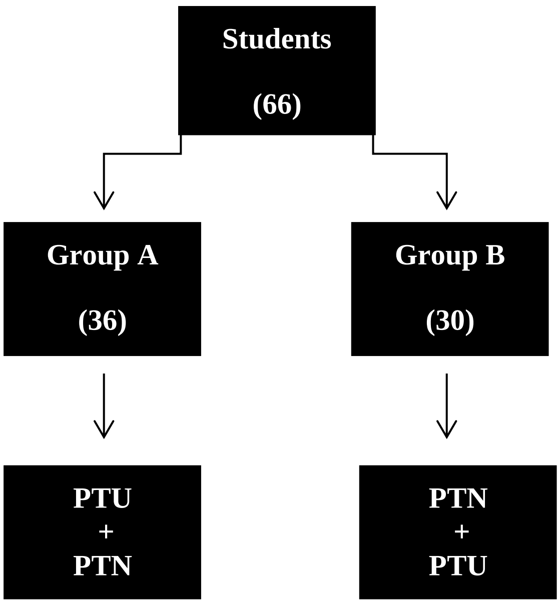


Figure 8 : Showing Study design, number of participants & Preparation sequence in each group

The data was collected via a standardised form. During preparation, the students were asked to fill out a data sheet (Fig.9), in order to record their seat number, previous clinical experience, any procedural errors recognised by them visually, the preparation time, preference of filing systems and also any comments including the file which had created the error or separated in the canal.

Advanced Endodontic Course Data Collection

Group 1

Student seat number		Please ensure that this number tallies with the numbering on your blocks

How many canals have you prepared on the clinic prior to this course?	
Can you state how many of these were prepared with hand protaper?	
If not all with protaper what other preparation method was used ?	

Preparation Type	**Was the block prepared successfully without procedural error? (tick= yes, cross=no)**	**Preparation time (please record in minutes)**	**If not please tick the errors) which occured**	**Ledge**	**apical zip**	**separation**	**canal transportation**	**over preparation**	**Please record details of any error(s), in particular the file which created the error(s), it's position and the consequence of this error in block preparation (i.e. Could the instrument/ledge be bypassed? Did you need to start a new block?) please keep all blocks if you need to prepare another**

Figure 9: Data Collection form

In order to allow outcome assessment, all the prepared blocks were labelled with a coloured dot system which was linked to a spreadsheet which contains the preparation technique for each block. That allowed blind assessment by the observers. Images of the blocks were captured under magnification of 3X using a digital camera attached to a microscope. For standardisation, all blocks were mounted onto a pre-marked graph paper to ensure the exact position of each block and reduce the effects of shadowing on the appearance of the root canals. The graph paper was attached to the top of X-ray viewer box, which was used as a source of trans-illumination below the block to increase the lighting and help in making the simulated canals more visible.

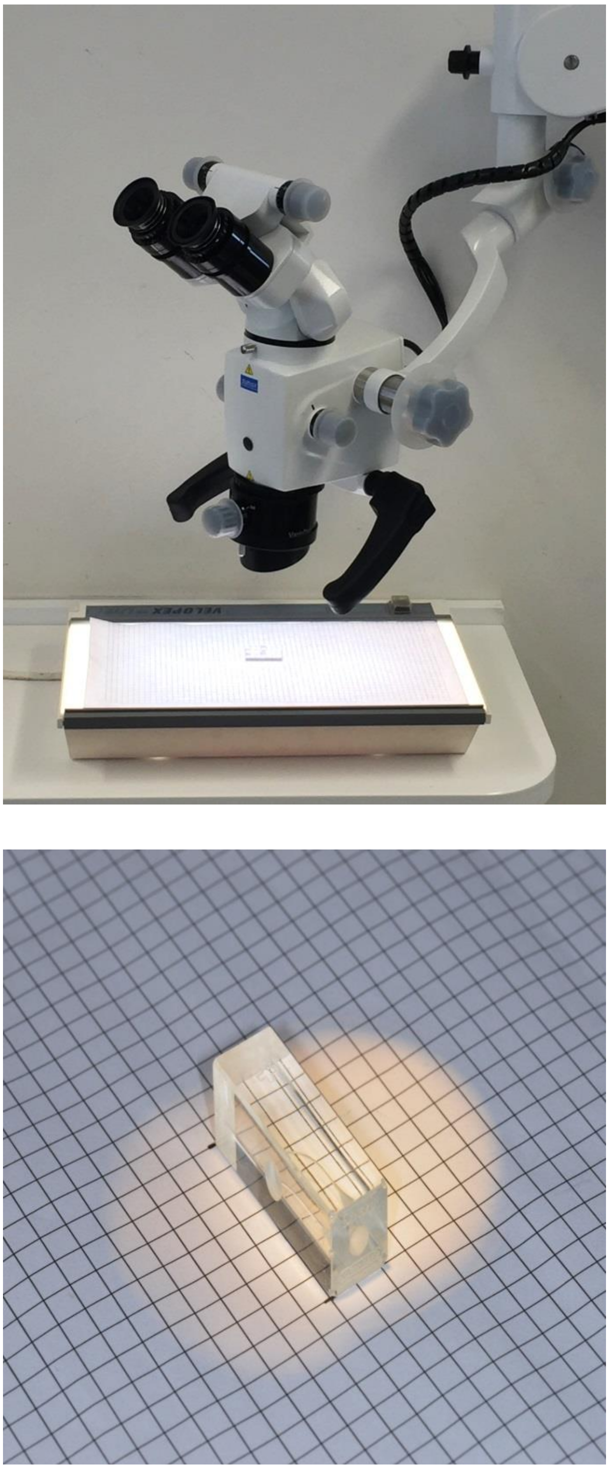


Figure 10: Laboratory configuration of equipment used to capture digital images

All images captured included the entire canal and the colour dot system of labelling. These pictures were downloaded onto separate USB data sticks for analysis separately by two observers. Digital images were assessed for ledges, apical zipping, separated instruments, canal transportation and damage to apical foramen as described by the criteria used below (Hülsmann *et al.*, 2005a):

- Ledge: Ledging of the root canal may occur as a result of preparation with inflexible instruments with a sharp, inflexible cutting tip particularly when used in a rotational motion. The ledge will be found on the outer side of the curvature as a platform, which may be difficult to bypass as it frequently is associated with blockage of the apical part of the root canal. The occurrence of ledges is related to the degree of curvature and design of instruments.
- Apical Zip: when the apical foramen became an elliptical shape and was transported away from the curve of the canal, also resulting in elbow formation coronally to this, where a clear narrowing of the canal can be seen (Gutmann and Lovdahl, 2011).
- Separated Instrument: is noted when a fractured rotary instrument was visible within the canal. Dependent on which stage this occurs, the file would either need to be removed if it prevents adequate cleaning of the canal or the canal, will be sealed over the fractured file, if it had already been adequately cleaned.
- Canal Transportation: is noted when the portion of the canal apical to the curvature is more prepared on the outer curvature (Cohen and Hargreaves, 2006). This also tends to occur when inflexible shaping instruments are used incorrectly.
- Damage to the apical foramen: Displacement and enlargement of the apical foramen may occur as a result of incorrect determination of working length, straightening of curved root canals, over-extension and over-preparation.

Using the above descriptions, preparation was considered successful, if none of the above procedural errors was noted, and preparation was considered failure, if one or more of the above procedural errors were detected.

The digital images of the blocks were analysed by 2 observers separately. The 2 observers disagreed on 17 images out of 132 (12.9 %).The 17 images were analysed by a third observer as a moderator, to decide on presence or absence and the type of errors.

3.3.1 Statistical analysis:

The raw data was collected and entered in Microsoft excel 2010 and then transferred to SPSS statistics 22 for statistical analysis. A generalised mixed model applied to the data to check for influence and significance of different fixed variables on the presence or absence of procedural errors .A univariate analysis test was applied to the data to check if the difference in time of preparation between the two file systems is significant.

3.4 Results:

Figures 11 and 12 showed examples of images taken for the resin blocks with different procedural errors.

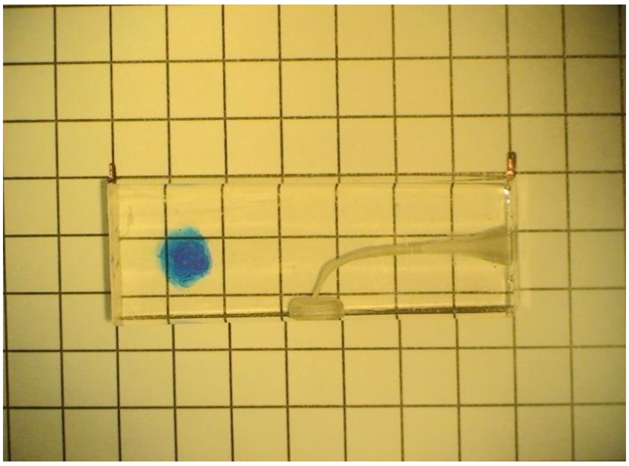


Figure 11: Ledge

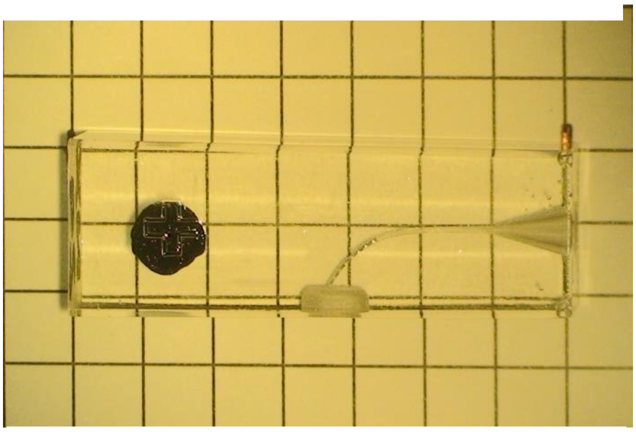


Figure 12: File separation

The total number of resin blocks, which were available for analysis was 132. Four blocks were excluded, 2 due to unprepared blocks with any file system and 2 blocks had no label to identify the file system.

<u>Frequency of success and Failure by File system</u>

File System	Success	Failure	Total
Rotary ProTaper Universal	24	40	64
<u>Percentage</u>	37.5 %	62.5 %	
Rotary ProTaper Next	57	7	64
<u>Percentage</u>	89 %	11 %	
<u>Total</u>	81	47	128

Table 1: Frequency of success and failure preparations in PTN & PTU file systems.

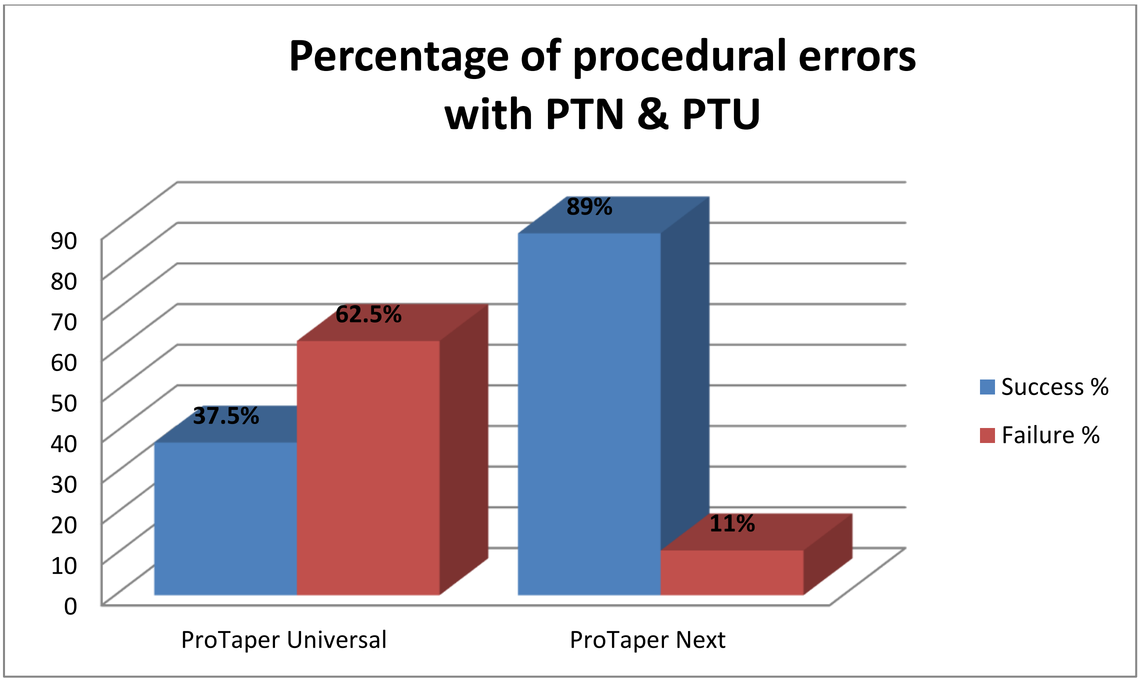


Figure 12: Successes and failure of ProTaper Universal and ProTaper Next preparations by UG students on resin blocks.

Table 1 and Figure 12, shows the frequency of success and failure with preparations done with different file systems after assessment of all blocks. It is clear that ProTaper Universal file system had the highest failure rate which was 62.5 % compared with ProTaper Next which exhibited only 11 %. In total 47 simulated canals out of 128 had procedural errors ,40 of them were in canals prepared with PTU and only 7 in canals prepared with PTN.

Generalized mixed model To test significance of different variables on procedural errors				
Variables	**F**	**df1**	**df2**	**Significance Value**
File system	93.748	1	122	0.001
Order of Using file systems	2.328	1	122	0.130
Number of canals prepared before	0.380	1	122	0.539

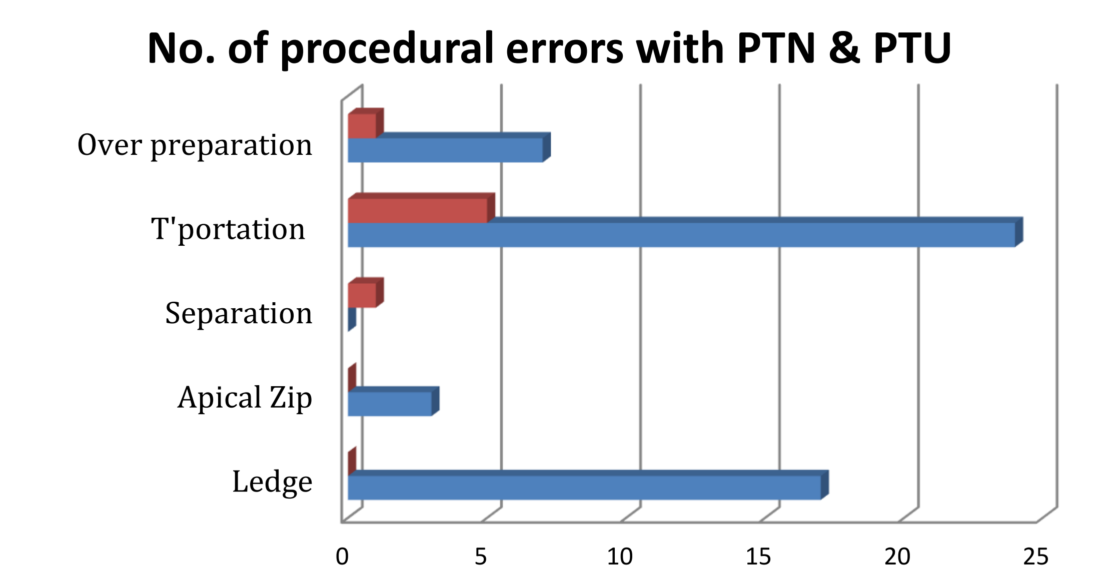
Table 2: Different significance values of multiple variables

The data were analysed using a mixed statistical model with type of file system, order of file system used and users' experience were set as fixed variable. The users' experience was determined by the number of canals prepared by hand instruments before taking part in the study. The model showed that only the file system had a statistically significant effect ($p<0.001$) that is associated with higher incidence of procedural errors.

<u>Incidence of Procedural Errors by File system</u>

Error Type	Rotary ProTaper Universal	Percentage	Rotary ProTaper Next	Percentage
Ledge	17	33.3 %	0	0 %
Apical Zip	3	5.8 %	0	0 %
Separation	0	0 %	1	14.2 %
T'portation	24	47 %	5	71.4 %
Over Preparation	7	13.7 %	1	14.2 %
Total	51		7	

Table 3: Number and type of errors with PTN & PTU.



	Ledge	Apical Zip	Separation	T'portation	Over preparation
ProTaper Next	0	0	1	5	1
ProTaper Universal	17	3	0	24	7

Figure 13: Graph showing the number of errors with PTN & PTU.

Table 3 and Figure 13 showed the incidence of procedural errors created by both file systems. ProTaper Universal file system showed a wide variation of error types with the highest being the transportation procedural error (47%) and the lowest being apical zipping procedural error (5.8%). There was only 1 file separation recorded with PTN file system.

The ProTaper Next file system showed a clear difference in error types recorded. Transportation was the highest type of procedural error (71.4 %) compared with separation and over-preparation procedural errors, where both scored (14.2 %). ProTaper Next showed no ledges and Apical zipping errors. Both file systems showed high tendency to cause canal transportation compared to other types of errors.

Time Taken for preparation with each file system

Time taken for block Preparation (Min ,Sec)	Rotary ProTaper Universal PTU	Rotary ProTaper Next PTN
Mean preparation time	13:32	9:22
Standard deviation	4:53	3:53

Table 4: Preparation time taken with PTN & PTU.

Table 4 showed the mean preparation time taken to prepare simulated root canals. The mean time taken for preparation using PTU was 13.3 minutes, while the mean time taken for preparation using PTN was 9.2 minutes.

Univariate ANOVA: time of preparation			
Factors	**df**	**F**	**Significance Value**
File system	1	51.332	0.001
Order	1	1.633	0.207
Student	63	2.878	0.001

Table 5: Univariate analysis of variance (ANOVA) to test for influence of different factors on the preparation time.

Table 5 showed the effect of different factors such as file system, order in which file system was utilised by the students and the students' skills and experience. The analysis showed that the file system variable had a statistically significant value of ($p<0.001$) which indicates that the type of file system affects the time preparation.

3.5 Discussion:

The aim of this study was to evaluate the influence of NiTi file systems on the canal shaping outcome and the incidence of procedural errors, in hands of novice operators (UG). Different studies have looked at technical differences between both NiTi File systems, such as ability to instrument the canals and the difference in mechanical and physical properties of both files (cyclic fatigue resistance) (Capar *et al.*, 2014b, Elnaghy, 2014, Pérez-Higueras *et al.*, 2014), but unfortunately no one has yet investigated operator experience and its influence on the instrumentation outcomes of these particular file systems.

The findings showed a remarkable difference in the incidence of procedural errors with ProTaper universal File system compared to ProTaper Next file system, it also showed a significant difference comparing the time needed for canal instrumentation, with ProTaper Next being more time efficient. Based on these findings the null hypothesis stating that there is no difference between the two nickel titanium file systems is rejected.

Both file systems showed the tendency to cause canal transportation, with ProTaper Universal system having higher incidence. ProTaper Universal also showed high tendency to cause ledges. The tendency of canal transportation is a common error to observe with most of the rotary NiTi files, especially the large sized, rigid instruments in curved canals (Capar *et al.*, 2014c). The shape memory effect pushes the file to try and straighten itself inside the canal when it goes around curvatures. ProTaper Next is made from a different phase of the nickel titanium alloy (M-wire) and has different design, which makes it more flexible and is able to negotiate canal curves more easily. In addition both files are manufactured in different phases of NiTi alloy, which are the austenitic phase for the ProTaper Universal and the martensitic phase for the ProTaper Universal. Specific design features explain the difference in the frequency of canal transportation errors between the ProTaper Universal and ProTaper Next. Our findings also agree with the established findings in the literature stating that ProTaper

Next causes less canal transportation and tends to prepare canals better around the curves in both extracted teeth and simulated canals (Gagliardi *et al.*, 2015, Wu *et al.*, 2015).
The study design (randomised crossover design), was chosen to try and minimise the amount of variation between the students and make sure that all the students participating have an equal chance to use both files with the same ability and within the same environment, however the order in which the file systems were used might still have an influence on the preparation outcome simulated canals. Therefore the order was taken into consideration as a co-factor during the analysis of the data. Two different assessors carried out the assessment and both of them were blinded to the type of file used to avoid any bias in the process. However there is a risk of bias during the assessment procedure, due to variability between different observers. That can be tested and rectified by applying inter and intra observer variability tests, if the same study design is conducted in the future.

Clearly the use of simulated canals in resin blocks does not imitate the exact scenario in root canals of real teeth, due to difference in surface hardness between the resin and the dentine (Lim and Webber, 1985b).This may account for the higher incidence of procedural errors we see with both file systems compared with studies in dentine/extracted teeth.. Some studies showed different efficiency and cutting ability of nickel titanium instrument in plastic compared to extracted teeth and it is postulated that instruments tend to attach more to plastic compared to dentine, which might lead to higher failure incidence than is seen with extracted teeth (Bryant *et al.*, 1998, Kazemi *et al.*, 1996). However based on other studies in the literature it was found that the simulated canal in resin blocks are valid experimental models and there is no significant difference between them and the extracted teeth during instrumentation, also in comparing plastic teeth to extracted teeth studies showed no influence on the technical outcome of the root canal treatment (LaTurno *et al.*, 1984, Lim and Webber, 1985a, Qualtrough and Dummer, 1997, Qualtrough *et al.*, 1999, Tchorz *et al.*, 2014) .This would suggest that the results showing the difference between the two file systems won’t change remarkably if the study was applied on extracted human teeth.

Considering educational and preclinical training in endodontics the use of simulated canals in resin blocks was shown to be utilised in multiple dental schools in different areas of the world, such as UK, Europe and the United States (Dummer, 1991, Qualtrough and Dummer, 1997, Qualtrough *et al.*, 1999). The simulated canals in resin were considered an addition to the teaching value, they aided particularly in illustration of mechanical preparation and emphasising the principles and the manner in which the instruments act to prepare the canals (LaTurno *et al.*, 1984). The use of simulated canals also allows us to have a reliable baseline and ensure the comparability of both file systems and enhanced the internal validity of the study. Extracted teeth will have multiple variations, such as degree, location and radius of the curvature as well as the shape, the length and the size of the canal. All these anatomic biases will have an effect on the outcome. In order to try and over-come the potential for variability, the need for a larger sample size is mandatory, however having a very large sample size if not calculated well, might affect the outcome and show unrealistic significance. This happens because it can exaggerate the comparative values, which makes it easier to find significance statistically.

Simulated canals are also easier to investigate for mechanical shaping and procedural errors, with different methods such as visualising under magnification or superimposing a pre and postoperative x-rays of them and detect the differences. When it comes to extracted natural teeth the procedure for comparison is much more complicated, they require teeth sectioning which is a destructive method and cannot be reversed or teeth clearing which is a complicated procedure and is time consuming.

A fairly recent development in Computed Tomography (CT) imaging is Micro CT, which is a very accurate method for defining differences in geometrical dimensions compared to the previous methods (Ordinola-Zapata *et al.*, 2016, Versiani *et al.*, 2011) . It is a non-destructive method; however the equipment is very expensive and scanning teeth and acquiring images is time consuming especially with a large sample size; it also needs powerful and highly complex software packages for image analysis. In addition an experienced operator with this, who has the knowledge and understanding of this technology needs to be conduct the process of scanning or guidance and help from specialists in this field is required. For these reasons, it is still not widely and frequently used in the field of endodontic research.

Based on the results obtained, the ProTaper Next file system appears to have higher incidence of producing successful mechanical preparations clinically in hands of clinicians with limited experience and will tend to be more time efficient. Different studies in the literature showed relevance between the operator experience and its influence on the technical outcome, time of preparation and instrument breakage. Practitioners with no experience and limited experience tends to be less biased towards a specific type of file system , however practitioners with high level of experience tends to have better technical outcome and being more time efficient (Baumann and Roth, 1999, Mesgouez *et al.*, 2003).

We still need to interpret the results carefully when attempting to extrapolate to the clinical environment, due to the limitations of simulated canals.

In the author's opinion it is important that students use a file system that has a lower incidence of causing procedural errors, because that will affect their perception and their preclinical learning experience and will help them in achieving successful outcomes. Producing successful preparations will have an influence on establishing clinical skill and gaining more confidence during the preclinical training phase, which will reflect on their educational progress and clinical outcomes in the future.

With a view to cost effectiveness, ProTaper Next will be more cost effective compared to ProTaper Universal based on the unit price per file and the clinical time saved during the procedure. Cost effectiveness may require a more profound way of investigation, it is still important for clinicians to have information about the different characteristics of the file systems they are utilising on everyday basis.

3.6 Conclusion:

Within the limitation of the study, in hands of novice operators, PTN showed a lower incidence of procedural errors and better time efficacy during instrumentation of simulated canals compared with PTU.

Chapter 4: Microcomputed tomography & three-dimensional image analysis

4.1 Introduction:

Microcomputed tomography (µCT) provides an accurate map for the absorption of x-ray radiation, whether there is a clear defined sub-structure of different phases or a slowly varying density gradient. The images acquired can be of a spatial resolution better than one micrometre (Landis and Keane, 2010). X-radiation has been used for a long time for radiological imaging. The concept is simple to use and apply to acquire images, however a lot of limitations are found. The images are not more than two- dimensional images showing the variation of absorption of x-ray within the object in study. The results are useful when the information needed is easy to identify and interpret. The problem with two-dimensional images is sometimes the exact positioning and dimensions of the objects can be compromised or missed. Another problem is when the object in study overlaps with another structure, that will have an effect on the radiation absorption between the different objects and some features might be completely missed from the image (Landis and Keane, 2010). Computed tomography or CT scans were introduced to try to minimise or solve these problems. The CT scan utilises a stack of two-dimensional images acquired from different projections, by both the x-ray source and capture sensor rotating around the object or the object rotating in front of the X-ray source.

The information gained from the projections is then combined and by using different algorithms depending on mathematical principles of tomography these images can be reconstructed in three-dimensions. Viewing the object in three-dimensions helps to exclude most of the surrounding noise and view the external and internal structure accurately based on the different density and absorption of the x-radiation. That concept was introduced initially in medical CT scans and then micro-CT machines were developed over the years. µCT machines are only used for *in vitro* imaging, due to the high radiation dose and long scanning time (Stock, 2008). Different types of materials or samples with different dimensions can be scanned. Some machines are manufactured for industrial purposes to be able to accommodate samples with larger dimensions. Recently some companies, e.g. Bruker have introduced the SkyScan in vivo µCT scanners, which can be used for laboratory animals.

Microcomputed tomography or micro-CT (µCT) is an imaging methodology, where individual projections recorded from different viewing directions are used to reconstruct the external and internal structure of the object of interest. The µCT machine works in a similar way as the medical CT. The images are collected in the form of slices, but in a much higher resolution compared to the medical CT. The resolution can reach up to 0.5 microns with some machines (Bruker, 2013). All the images and data acquired are reconstructed in a three dimensional manner. The µCT acts as a 3D microscopy, where very fine details of the internal structure can be visualised and analysed without being invasive or destructive to the sample. The advantage of µCT compared to histology or teeth clearing in endodontics is that the same sample can be inspected and analysed multiple times without destruction during the process of either mechanical manipulation or different tests

In µCT information from the two-dimensional images are combined and reconstructed to form a three-dimensional images. µCT images can encounter different problems and limitations, which can affect the accuracy, precision and clarity of the image. Reconstruction software must cope with different artefacts and noise that occurs during the experimental imaging (Stock, 2008). Positioning errors are a major issue, ideally the µCT machine should have the component errors much smaller compared to the smallest voxel size specified, that will help the software to apply field correction and extract the highest quality data possible.

The accuracy of the µCT reconstruction has been investigated in many papers and the slices have been compared to physical sections. The studies unequivocally demonstrated that the µCT reconstruction are very accurate, however some limitations were also identified (Stock, 2008). The limitations are related to the understanding of the technique and how to apply it and how to interpret the data and information acquired. Also having the knowledge and the appreciation of what can be detected and resolved is very important. There are multiple factors such as spatial resolution, contrast, linear attenuation coefficient, field of view and also the different parameters to apply from the x-ray source during the experimental imaging, these factors will have a major effect on the data reconstructed and the quality and quantity of information that can be collected.

Different errors such as, under sampling and reconstruction centre error, and some artefacts such as motion artefacts, ring artefacts, beam hardening, streak artefacts, and phase contrast artefacts, can happen during the scanning processes. Most of these artefacts will have an effect on the quality of reconstruction, some can be corrected during the reconstruction process and some can have a significant effect on the image quality (Stock, 2008).

Motion artefacts occur due to minor movements of the sample during the projections. As the projections are collected with very high magnification to view very fine details, the movements can still be very minimal but have a significant effect on the image, causing it to be unrecognised in some situations. It is also more of a problem with soft tissue specimen as they are influenced by relaxing of the tissues, gravity and some drying of the tissue.

Ring artefacts occurs during the image projections, and have an influence on viewing the images. They also interfere with the accuracy of the segmentation processes and quantification of the different phases of the samples in their dimensions and geometry. Ring reduction can be achieved by applying different types of filters through the reconstruction software, some of these filters can helps achieve good results. Using the correct type of filters, showed to have a significant effect on the reduction on the ring artefacts and noise compared to the non-corrected images (Davis and Elliott, 2006, Stock, 2008).

Beam hardening is another artefact and one of the most common artefacts seen with tomography system using a conventional x-ray source emitting polychromatic x-ray beam. As the x-ray beam attenuates the sample appears less dense in the middle compared to the outer borders.

Beam hardening combined with scattering can cause cupping effect artefact. Trying to decrease the extreme variation of the beam energy in the polychromatic x-rays can assist in dealing with beam hardening; this can be achieved by physical filtering such as aluminium or copper. An alternative way to deal with beam hardening is by correcting the images during the reconstruction by applying a linearisation curve to minimise the effect happened due to the difference in absorption of the radiation at the centre and the borders of the specimen.

Streak artefacts, are a non-physical streaks that show the same scattering effect on the image and radiate from high-absorption object with in the sample. Under sampling and reconstruction centre error are related to the field of view, degree of step rotation of the sample during the image projection and the accuracy of the centring of the sample during the collection of the projections. Appreciating the sample dimensions and applying enough safety margins and the right degree of rotation will minimise or exclude the under sampling issue. The reconstruction centre error is solved by a re-centralising algorithm that helps to minimise the error and make sure that it picks the best uniform centre from the slices during the stitching and reconstruction of the images.

It is important to resolve any potential artefact or errors to achieve accurate and reliable images. This can be achieved by extensive testing prior to conducting any experiment. It is imperative to pilot different parameters and correction tools to optimise the images before *in vitro* testing.

4.2 Image analysis:

Image analysis is the phase following acquiring and reconstruction of the images. Image analysis is conducted for different purposes such as, visualisation, measuring, quantitative or qualitative analysis, three-dimensional assessment and design. Many image analysis software packages are available with different capabilities and tools. Some of them are single software capable of doing all the required functions and some of them are packages combining multiple software, each one for a specific stage in the analysis process. Some software is very powerful and of high accuracy and some are very basic in their functions and their accuracy is not well verified (Stock, 2008)

Working with images and reconstruction for three-dimensional models, accuracy becomes a major concern. The accuracy is initially and highly influenced by the scanner images and other parameters, that should be taken into consideration as mentioned previously in this chapter. Another secondary influential factor is the software used to reconstruct and analyse the images. After investigating and trialling different software packages, the Materialise software package *(Materialise N.V., Leuven, Belgium),* was chosen, for being powerful and with high capabilities. The two main software used from the package are Mimic (*Materialise N.V., Leuven, Belgium)* for image segmentation, quantitative analysis and three dimensional model reconstruction and 3Matic (*Materialise N.V., Leuven, Belgium)* for the three dimensional models superimposition and comparison analysis. The accuracy of the software has been verified and showed to be highly accurate in comparison with histological sections and live measurements. The investigation of the package was done through multiple independent studies not influenced by the software company (Gelaude *et al.*, 2008, Jamali *et al.*, 2007, Moerenhout *et al.*). The process starts with segmentation and reconstruction of the three-dimensional model, both were carried out with Mimic software. The second stage was the superimposition and the comparison analysis, and these were done with 3Matic software.

Image segmentation is the process of dividing into a multiple segments or different groups of pixels. The aim of segmentation is to simplify the digital image into a simpler form of data that can be visualised or analysed (Shapiro and Stockman, 2001). The segmentation defines a group of pixels of a specific tissue or object of interest to be marked and then reconstructed as a three-dimensional model for further analysis. There are multiple ways of doing the segmentation the standard way is the thresholding method, where a grayscale range is defined between two threshold values. The other two methods are edge-based methods and region based methods. The method is picked based on the images and the quality and how different the pixel values are from each other and if they are easy or difficult to separate. An example is shown in Figure 14. The segmentation process is a very critical step in image analysis, because it decides the structure of interest and influence the qualitative and quantitative analysis to come after (Fourie *et al.*, 2012, Xi *et al.*, 2014)

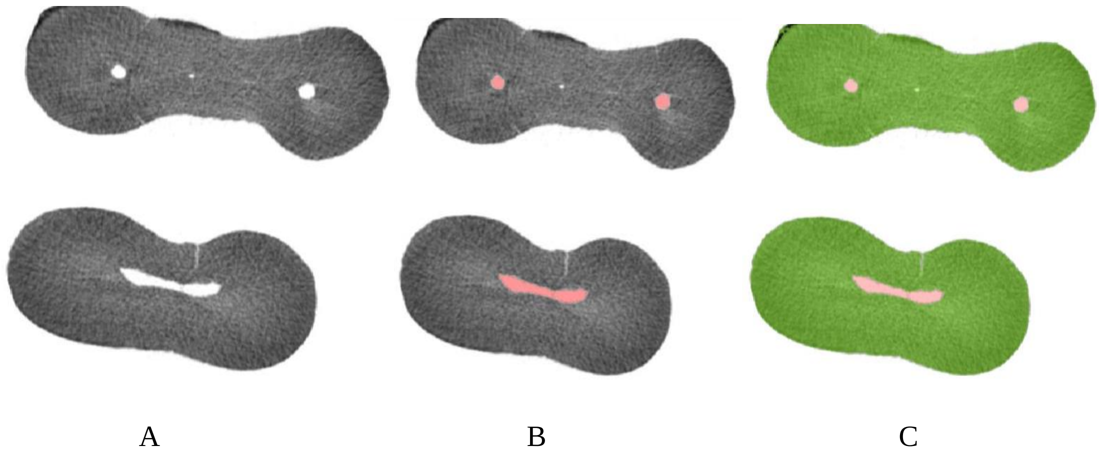


Figure 14: Illustrates segmentation process and the application of different masks to the image in order to prepare for segmentation.

A) Showing no masks applied.

B) showing a mask applied in red colour to segment the root canal space.

C) Showing 2 masks applied to segment the root canal space in red and the root structure in green.

The second stage is the three-dimensional model reconstruction, and is undertaken by the mimic software utilising complex mathematical algorithms called marching cube algorithm. Basically the software takes the outer contour of the created mask in every image and interpolates between them using triangles. Then the algorithm generates a triangular surface that approximates the ISO-surface at a given threshold, through a 3D grid of gray values. The software gives the option of having different quality 3D object presentation, the higher the quality the longer the time needed for calculations of the 3D objects and the higher the accuracy of the object dimensions and representation. The software uses two different algorithms to produce a 3D presentation with higher accuracy; they are called the interpolation algorithm and contour algorithm. The type of algorithm to use can be chosen according to the tool and depending on the type, accuracy and dimensions of the 2D slices. Each algorithm provides higher accuracy in a different situation. The accuracy of the software in the 3D calculating procedure has been investigated and proven to be of a very high accuracy (Gelaude *et al.*, 2008). With the mimic software the three-dimensional model provides plenty of information about the object of interest, such as number of pixels, surface area and volume. The three-dimensional models are then transferred to the 3matic software to be super-imposed and then analysed comparatively.

The 3matic software is mainly used for different types of analysis, measurements and design. Super-imposition is the first step to carry out with the software. There are multiple ways of aligning and superimposing the objects of interest, some of them are manual or semi-automated and some are fully automated by the software, with the aid of mathematical algorithms. The manual tools are based on movement of the objects by the operator in three dimensions to try and get the objects aligned as much as possible based on visualising and comparing the alignment of the outer borders and the different colours of the two objects. The automated tool utilises different coordinates and the outer borders as well to align the objects. The tool also shows the difference error between the alignments of both objects. The accuracy and the number of iterations applied by the tool can be modified manually to achieve the best results. The process is applied multiple times, utilising different tools available to check if the outcome is the same each time. The process can be time consuming, but it provides confidence that the outcome is highly accurate. The software demonstrated very high accuracy in the super-imposition of the objects. The error detected was less than one voxel or even better. The one voxel represents the scan resolution, so if the scan resolution is 20 microns the error detected based on the difference error calculated and reported by the software will be less than 20 microns.

The second step done by the software was applying comparative analysis between the objects. The software applies different algorithms to compare between the changes happened to the object before and after the mechanical manipulation. The idea is to verify the difference between the static and dynamic voxels to calculate the difference between the two 3D objects. The voxels are the units building the three dimensional image. Some of these voxels stay the same when comparing the pre-operative and post-operative three dimensional image, these are called static voxels. The dynamic voxels are the ones that changed in comparison between the pre and post-operative images. The output is in a form of a histogram segmented into different values and colours, showing the amount and place of dynamic voxels in different areas through the objects. The histogram shows different percentages in each area depending on the changes happened to the voxels between the 3D objects before and after the manipulation. In order to verify the applicability of the software capabilities and functions to the planned study, a pilot study was conducted to check if we could achieve the required outcome.

4.3 Pilot study:

4.3.1 *Introduction:*

The µCT imaging and analysis were utilised in many different studies in the field of dentistry in the past and more specifically in endodontics. Many different aspects were investigated utilising this technology. Some studies investigated morphology or anatomical features (Plotino *et al.*, 2006, Swain and Xue, 2009, Versiani *et al.*, 2011), other studies investigated geometrical, structural changes, procedural errors and the effect of the mechanical preparation on root canal systems (Capar *et al.*, 2014b, Habib *et al.*, 2015, Peters *et al.*, 2001a, Peters *et al.*, 2001b, Swain and Xue, 2009).

There are plenty of challenges encountered during utilising the µCT technology. Generally the µCT scans is known for the long scanning time. Achieving the balance between acquiring high quality images and reasonable scanning time is the initial challenge. It is influenced by multiple factors, such as understanding and having the knowledge of the type of material to be scanned, the scanning parameters and their effect on the image quality and the time of scanning.

The other aspect is choosing the image analysis software, which has the capability to analyse the object of interest, whether it is a qualitative or a quantitative analysis. The accuracy of the scan and the software used to analyse is also very important. All these aspects are subject to long learning processes with a lot of trial and error, depending on the amount of experience of the operator. A pilot study was designed to investigate all these aspects mentioned previously to reach the best protocol for conducting the *in vitro* study described in chapter 5.

4.3.2 *Aim:*

The aim of this study was to investigate if the mechanical preparation done within the root canal system of the teeth by different rotary endodontic file systems can be detected and analysed; utilising the µCT imaging and materialise software package for image analysis.

4.3.3 Methodology:

The trial was conducted on a single mandibular molar. The initial step was choosing the suitable scanning parameters for the µCT machine (SkyScan 1272, *Bruker Corporation)*. Several scanning parameters were trialled based on previous studies from the literature.

The aim was to achieve a high quality image showing the required information and a scanning time between thirty to forty minutes, the major parameters that were calibrated were the resolution, x-ray power, and degree of rotation of the sample, type of filtration and reconstruction parameters.

One of the main factors that is affected by the resolution is the field of view (FOV) the higher the resolution the smaller the field of view. The field of view has an effect on the scanning time, if the FOV is small the scanner will have to do multiple scans to cover the object of interest and that extends the scanning time by two or three times depending on the resolution. About ten different combinations of these parameters were trialled, until an image of high quality and the required scanning time was achieved.

The molar was placed in a 5 cm plastic syringe, which was tight enough to make the molar stable in place during the scan as shown in Figure 15.

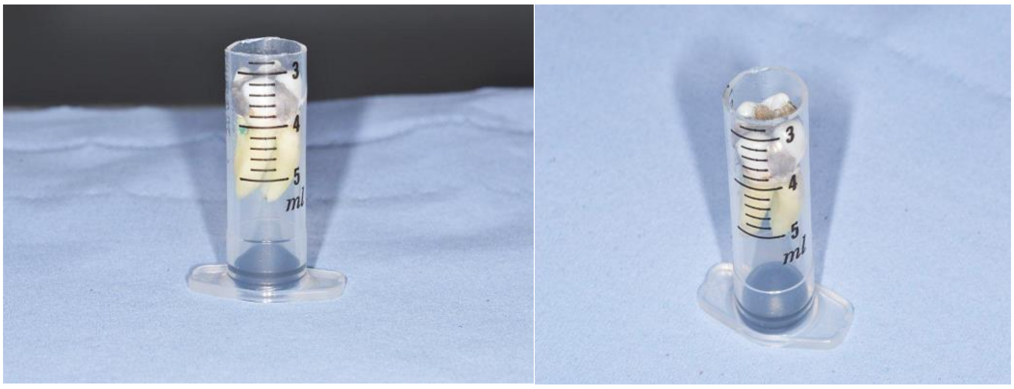


Figure 15 : Plastic syringes used to hold the molars to be fitted in the µCT machine.

It was fixed to the standard holder that comes with the µCT machine to be fitted inside the scanner. The plastic syringe was only used as a holder during the calibration phase, until the suitable protocol and scanning parameters were established. The plastic syringe wasn't a problem at the calibration phase, because there was no comparison between preoperative and post-operative images, otherwise it can have an effect on the accuracy of the superimposition and the analysis of the results. A custom made holder was then fabricated to accommodate the molar for scanning and to confirm the molar is placed in the exact same position between the different scans, shown in Figure 16.

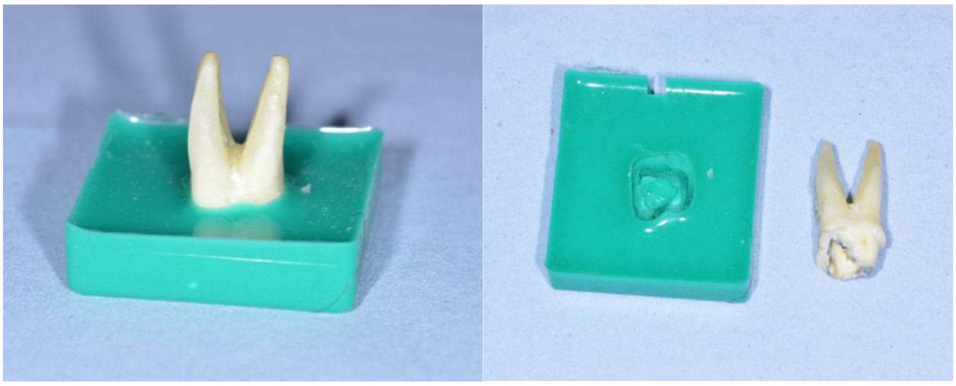


Figure 16: Custom made holders made from silicone to hold the molars in place during µCT scanning.

The fabrication of the custom made holder needed some trial and error. The challenge was finding a rigid material that can keep the sample secure in place during the scan with no movement what so ever and not to get distorted while removing and placing the sample multiple times to ensure the accuracy of the position at every scan. The other side of the challenge is that molars or teeth in general have undercuts in their structure, so the material needs to be forgiving to allow the molar to go in and out. Different materials were tried such as acrylic, wax, rubber, silicone and addition-vulcanizing duplication silicone (Z-DUPE, HENRY SCHEIN®) was chosen. The material is used for duplication technique for laboratory impressions in the dental field and was satisfactory for being rigid enough to hold the sample stable during the scanning procedure and not to distort with repetitive removal and placement of the sample.

The molar was fitted in the custom made holder and placed in the µCT scanner to be scanned preoperatively with the established parameters. The scan was done with the following parameters 20µm, 142 µA, 70Kv, 180° of rotation with 0.5° step of rotation and 0.5 mm aluminium filter. The total time of scanning was 27 minutes per sample. The image was reconstructed with the following parameters; ring artefact reduction of 6, smoothing of 1 and beam hardening correction of 30%., Using NRecon reconstruction software provided with the µCT scanner.

The molar was then accessed and mechanical preparation undertaken with the NiTi rotary file system XP-endo Shaper *(FKG Dentaire SA, La Chaux-de-Fonds, Switzerland)* size 0.30 mm, 1% taper and a tip of 0.15 mm, which achieves preparation of size 0.30 mm, 4 % taper and sodium hypochlorite used as an irrigant. The sample was then placed back in the custom made holder and placed again in the scanner for the post-operative scan. The molar was scanned again utilising the exact same protocol as the pre-operative scan.

The pre and post-operative images were reconstructed with the same protocol and then transferred to a different computer to utilise the Materialise software package for analysis. The image stack was imported to the Mimic software to apply the first phases of segmentation and three dimensional reconstruction. The gray scale values were modified, until an image with very minimal or no noise is achieved.

Segmentation process was then applied trying different tools and the best results were achieved with the region-growing tool. The other tools for segmentation had multiple problems. The main issue using the thresholding was segmenting the root canal space without including the air space around the molar, because they had the same values and cleaning the generated mask or 3D model, used to consume a lot of time and influence the accuracy. The dynamic region-growing tool solved this problem by giving the flexibility of which area to apply the threshold and the accuracy of picking the areas to be included in the segmentation no matter how small it is. The mask generated by the segmentation tool was visualised and inspected to make sure all the area of interest is included. Once the segmentation process was satisfactory, a three-dimensional model was computed and generated by the software showing the preoperative root canal space of the molar. The same protocol was applied to the image stack of the post-operative images.

Both 3D models were then transferred to the 3matic software for the second phase of the analysis, which is superimposing the pre and post 3d models of the canal space and apply a comparative analysis.

The superimposition of the 3D models can be done by multiple alignment tools. At the start the problem was getting a high accuracy of the super imposition, because it will have an influence on the comparative analysis. The manual and automated tools were trialled each by itself and combined, until the satisfactory combination that showed consistent accurate results was figured out. Using the manual method first until achieving the best position visualised by the operator, helps in simplifying the process for the automated tool and makes it more accurate. It is still a time consuming process compared to using the fully automated tool from the start.

The automated alignment is applied multiple times until the error reported values by the software is lower than one voxel or even less, in some occasion an accuracy of less than 0.2 microns can be reached, which is of a much higher accuracy compared to one voxel (20 microns).

After achieving the required superimposition, the comparative analysis tool is used to compare the differences between the 3D models. The tool allowed the operator to choose different 3D models for comparison analysis. The Post-operative model was chosen to be compared to the preoperative model, which is the original root canal space without any mechanical manipulation. A histogram was then computed and presented by the software to show different areas with different colours on the models. These areas were segmented into different percentages from the total structure and represent the amount of dynamic voxels compared to the static voxels. In a clinical context it reflects the amount of mechanical instrumentation applied to the canal walls inside the root canal system. The analysis was applied multiple times to verify if the percentages are consistent and accurate each time.

The required scanning parameters to have a good quality sharp images were achieved. The reconstruction parameters were modified until a high contrast images with minimal noise were acquired. Different tools of segmentation and thresholding were trialled until the required area of root canal space was segmented accurately and excluding any other airspace surrounding the tooth image utilising the region dynamic growing tool. The 3D models superimposition was achieved accurately utilising manual and automated tool. The comparative analysis tool was used to compare the pre and post-operative 3D models and the different areas and percentage of instrumentation.

4.3.4 *Conclusion:*

The pilot study showed a successful attempt of utilising the μCT technology for assessment and analysis of the efficacy of root canal instrumentation.

Based on the pilot study findings, a randomised controlled single blinded in vitro trial was designed to investigate and compare in mandibular molars the efficacy of two rotary NiTi file systems claiming to achieve high percentage of root canal instrumentation, while conserving the tooth structure.

Chapter 5: An investigation of the efficacy of instrumentation in Mandibular Molars using the XP-endo Shaper NiTi rotary file Vs ProTaper Next rotary file: A Micro CT Analysis.

5.1 Introduction:

The root canal system is highly complex; canal shape can vary from tooth to tooth and even between roots of the same tooth. Canals can be oval or C-shaped in cross-section; they sometimes split or join through an isthmus. Different studies, such as dye and micro CT studies have illustrated this complexity (Plotino *et al.*, 2006, Swain and Xue, 2009). This explains the difficulty in accessing or fully reaching some areas inside the root canal system. In the face of such complexity, standard nickel titanium files do not always achieve the ideal preparation during root canal instrumentation. Despite their flexibility and different movements inside the root canals, the files tends to create cylindrical shapes only, replicating their geometrical dimensions and thus cannot reach certain parts of the canal during mechanical preparation. Several studies involving micro CT technologies have shown that, when standard nickel titanium files are used to prepare the root canal, only 40-70 percent of canal walls are actually instrumented (De-Deus *et al.*, 2015, Peters *et al.*, 2001b). Various complementary techniques, such as the use of a high concentration of sodium hypochlorite (NaOCl) or Ethylene-diamine-tetra-acetic acid (EDTA) as irrigants with the aid of ultrasonic or lasers lead to a slightly better results, which can be improved if these root canal walls are mechanically instrumented, before applying these complementary techniques (Hülsmann *et al.*, 2005a).

Developing of a NiTi root canal instrument with high instrumentation efficacy has been of an interest to different manufactures. Different endodontic NiTi file systems were introduced recently, that claim to use single file as to conserve tooth structure. In 2009 the self-adjusting file (SAF) (*ReDent-Nova, Ra'anana, Israel*) was introduced (Metzger *et al.*, 2010). In 2015 TRUShape 3D Conforming File (*Dentsply International, Inc., USA*) (DENTSPLY, 2015) was introduced. Both files were adopting the concept of achieving three-dimensional shaping, while respecting the canal anatomy and preserving the root dentine. More recently XP-endo shapers (XPS) and XP-endo finishers (XPF) (*FKG Dentaire SA, La Chaux-de-Fonds, Switzerland*) (FKG, 2017) shown in Figure 17 were introduced.

A B

Figure 17: showing, (A) XPS file & (B) XPF file.

The files are made of a highly flexible nickel titanium alloy called MaxWire®. This NiTi alloy is a thermally treated alloy combining two different phases of the nickel titanium alloys in the file. The two different phases are martensitic and austenitic phases and transformation between both phases happens reversibly between when exposed to different temperatures. The XP-endo Shaper is in the martensitic phase in room temperature and transforms to the austenitic phase starting from a temperature of 35 degrees C shown in Figure 18.

Figure 18: showing the XPS file in the martensitic and austenitic phase

The File should transform to the austenitic phase when the file touches the root canal walls to prepare them. The XPS with ISO #30 in diameter and 1 percent taper and achieves a preparation of minimum size #30 and 4 percent taper and the XPF with ISO #25 in diameter and 0 percent taper. The XPS works with a new concept and described as adaptive core technology. This technology makes the core of the file expands horizontally and adapts to the canal wall anatomy and not like the conventional file systems, it moves freely inside the canal and only contacts the canal walls in one site. That helps in making the file more efficient, but without occluding the dentinal tubules and also facilitates debris removal. The manufacturer also claims that the file causes turbulence inside the canal due to the free movement and that facilitates the flow of the irrigant and the penetration inside the dentinal tubules. Another claim is that the file has high flexibility and high resistance to cyclic fatigue and also is very gentle on the canal walls and does not generate stresses and dentinal micro-cracks. The manufacturer claims that the XPS allow better mechanical preparation and better instrumentation efficacy of the canals in areas previously impossible to instrument, and that efficacy can go up to three times more than the conventional instruments. However there is lack of evidence in the literature to support the claims of the manufacturer

The XP-endo Finisher is mainly used as an anatomical finisher post preparation with any file systems with a minimum size of preparation of #25-30. The XPF is extremely flexible file and expands horizontally to contact dentine surface to scrape the walls and help in disrupting the biofilm, removing smear layer and debris in areas where the wider diameter files can't reach and without changing the original shape of the canal and preserving the dentine (FKG, 2015). In addition it enhances the irrigation process by agitating the irrigant and increasing the flow inside the dentinal tubules. The concept depends mainly on a very small diameter and 0 percent taper and high flexibility, which helps in fitting the file in a straight or a curved canal. Combining these characteristics with high rotation speed reaching up to 1000 RPM, helps in expanding the core of the file horizontally to increase the capacity of instrumentation up to a hundred folds of an equivalent sized file. Recent study has demonstrated the efficacy of the XPF in removal of debris and bacteria, colonised in dentinal tubules in comparison with conventional irrigation, sonic activation of the irrigant and laser activation (PIPS) (Azim *et* *al.*, 2016). The study compared 4 different irrigation protocols and their effect on bacteria inside dentinal tubules. They examined the penetration and effect of the irrigant by confocal laser scanning microscope. The 4 protocols were conventional needle irrigation, sonically activated irrigation, XPF activating the irrigant and erbium: yttrium aluminium garnet laser (PIPS). The assessment was measuring the quantity of live versus dead bacteria in the dentinal tubules. All protocols eliminated the bacteria significantly, But XPF had the greatest bacterial reduction in the 3 segments of the root (Coronal, middle, Apical) and PIPS showed highest deep penetration in dentinal tubules.

The endodontic literature lacked any evidence or studies investigating the shaping ability of XPS file and its effect on root dentine preservation. In addition no studies investigated the shaping ability of the XPF file and its ability clean canal walls and preserve dentine. Hence a study was designed to help investigate the abilities of those files

5.2 Aim:

The aim of this study was to investigate the percentage of root canal surface instrumentation and amount of dentine preservation achieved by XP-endo Shaper (XPS) rotary NiTi file ***(****FKG Dentaire SA, La Chaux-de-Fonds, Switzerland****)*** versus ProTaper Next rotary (PTN) NiTi file *(Dentsply maillefer)* in mandibular molars, using Micro Computed Tomography (µCT) imaging and three dimensional analysis.

A second aim was to investigate if adding the XP-endo finisher (XPF) rotary NiTi file ***(****FKG Dentaire SA, La Chaux-de-Fonds, Switzerland****)*** to the preparation sequence as a finisher file will increase the percentage of instrumentation , and if that will be different between the XPS file system compared to the PTN file system.

5.3 Null hypothesis:

There is no difference in the percentage of instrumentation achieved and the amount of dentine removed by XPS file compared to PTN file.

There is no difference between the amounts of dentine removed in the coronal segment by XPS file compared to PTN file.

There is no difference in the percentage of instrumentation achieved by XPF file after XPS file compared to the PTN file

5.4 Materials and methods:

5.4.1 Sample selection & standardisation:

The design of the study was as randomised controlled single blinded in vitro trial. The sample size was twenty-four mandibular molars, based on sample size from previous studies (De-Deus *et al.*, 2015, Paqué *et al.*, 2009, Paqué and Peters, 2011) . The teeth obtained from University of Liverpool tissue bank, after granting of University ethical approval. Standard plastic tubes were utilised to fix the Forty-seven mandibular molars in a predetermined position; these tubes helped in fixing the samples to the standard sample mounts provided with micro CT scanner, for placement inside the scanner. The samples were scanned to standardise the anatomy, dimensions, volume and degree of curvature of the root canal space, using (High resolution Micro CT scanner SkyScan 1272 *(Bruker corporation)* shown in Figure 19.

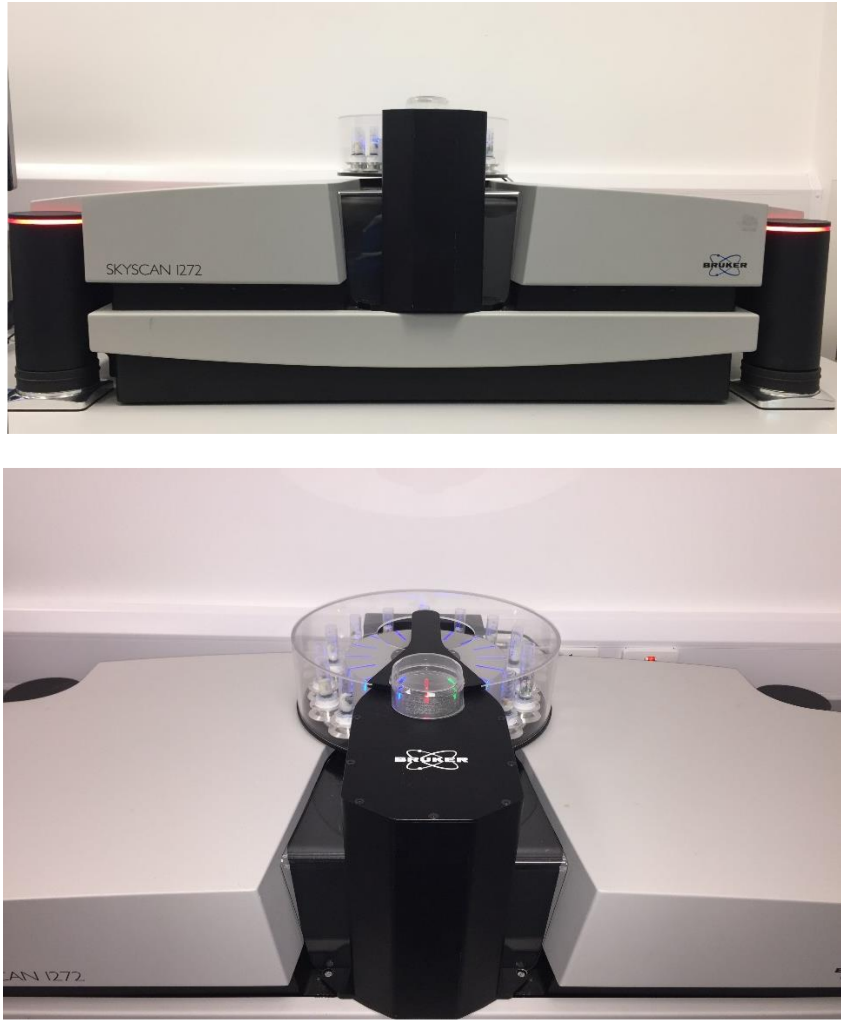


Figure 19: showing the Micro-CT machine used for scanning.

The scanning was done using a resolution of 26um, 180 degree of rotation and 0.5 degrees rotation steps, 0.5 mm thickness aluminium filter and the time of scanning was 30 to 35 minutes per tooth. The teeth were classified for anatomy as simple and complex based on their Vertucci classification of root canal system (Vertucci, 2005).

The canals degree of curvature was measured using Schneider's method (Schneider, 1971) and divided into 3 groups; which were less than 20 degrees curvature, between 20 to 40 degrees and more than 40 degrees curvature. The volume divided the canal space into three groups, small, medium, and large, after quantifying the volume by using the image analysis software. The canal dimensions divided the molars into two groups based on their bucco-lingual and mesio-distal canal dimensions. The molars were allocated to the normal dimensions group if the mesio-distal dimensions were less than 1.5 times the bucco-lingual dimensions and were allocated to the wide dimensions group if the mesio-distal dimensions were equal to or more than 1.5 times the bucco-lingual dimensions.

After categorisation twenty-four molars were chosen, each molar had a custom-made holder made to ensure that the molar had the same position for the pre-preparation and post-preparation scanning to help in accuracy of imaging and further in superimposing the images. The molars were randomised using stratified randomisation method, taking into consideration the anatomy, degree of canal curvature and canal dimensions and volume. The samples were encoded to avoid any selection or operator bias and then were split into two groups, Group 1 (G1) for XPS and group 2 (G2) for PTN. Each molar was scanned before undergoing preparation using (High-resolution Micro CT scanner SkyScan 1272) *(Bruker Corporation)* with a resolution of 20um, 180 degrees of rotation with 0.5 degrees of rotation step and a 0.5 aluminium filter, with scanning time of 45 minutes per molar.

5.4.2 Sample preparation:

The molars were instrumented after the pre-preparation scanning. Group 1 was prepared using XP-endo Shaper size 0.30 mm, 1% taper and a tip of 0.15 mm, which achieves preparation of size 0.30 mm, 4 % taper. After negotiating the canals and achieving patency using size 10 k-file and glide path using size 15 k-file, the preparation was done following the manufacturer protocol (FKG, 2017), using standardised amount of sodium hypochlorite irrigation, one millilitre and by a single operator. Group 2 was prepared using ProTaper Next, X1 file size 0.17mm tip, 4 % taper and X2 size 0.25mm tip, 6 % taper after achieving patency and glide path using size 10 k-file. Using standardised amount of sodium hypochlorite irrigation, one millilitre and by the same single operator.

The single operator was a senior postgraduate in the last year of his endodontics speciality training and was blinded to the preoperative images of the samples. The XP-endo Shaper preparation carried out in a water bath with the temperature controlled at 37 degrees Celsius, to resemble human body temperature. As the manufacturer mentioned that the file transforms from martensitic phase to austenitic phase when the temperature goes over 35 degrees Celsius. The setup was built to minimise any influence on the ability of the file to prepare the canal walls. Teeth were scanned post-preparation with Micro CT scanner with the same previous scanning parameters.

Both groups G1 and G2 had another preparation after the post-preparation scan. The preparation carried out by XP-endo Finisher NiTi rotary file, size 0.25 mm and 0% taper, by the same operator and using standardised amount of irrigation of sodium hypochlorite (1 millilitre). Both groups were prepared in a water bath with controlled temperature at 37 degree Celsius, as the file undergoes the same transformation between the alloy phases as mentioned previously with the XPS. Both groups were scanned again after the XP-endo finisher preparation, utilising the custom made holders and with the same scanning parameters.

5.4.3 Micro-CT evaluation:

All the data set of images underwent reconstruction using a software provided with the Micro CT machine called NRecon (Bruker Corporation) shown in Figure 20.

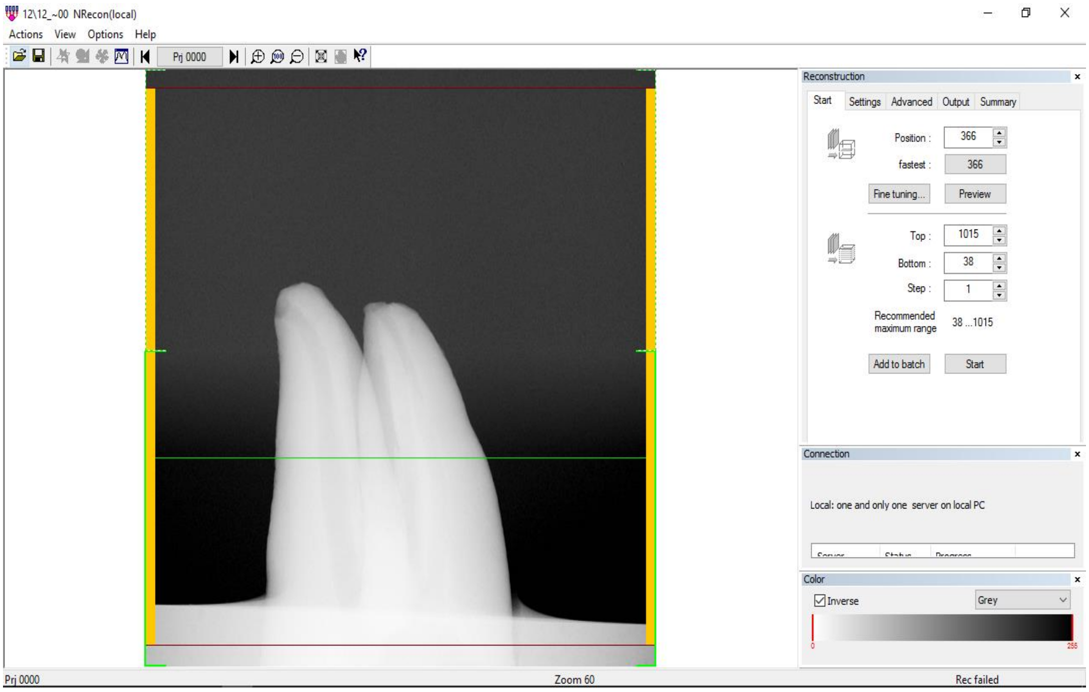


Figure 20: showing the interface of the NRecon software for data reconstruction

As shown in Figure 21 different parameters were applied to data during reconstruction, to reduce the artefacts and enhancing the images quality (Ring artefact reduction factor of 5, beam hardening correction of 30% and smoothing factor of 1).

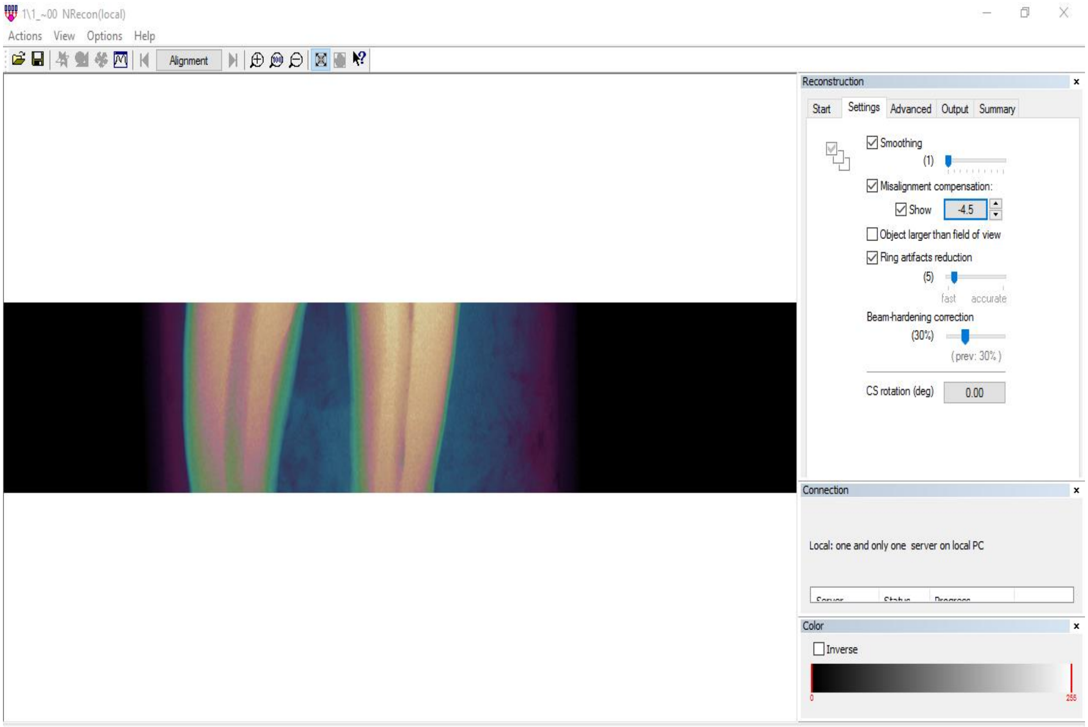


Figure 21: showing NRecon software interface with different reconstruction parameters.

A password encrypted external hard drive utilised to transfer and store the image data set. A software used for image analysis called Mimics *(Version 19.0*) shown in Figure 22, was used for data set importing, segmentation and three-dimensional reconstruction of the images for the three different datasets, the pre-preparation, post preparation for G1 and G2 and post-preparation with XPF for both groups.

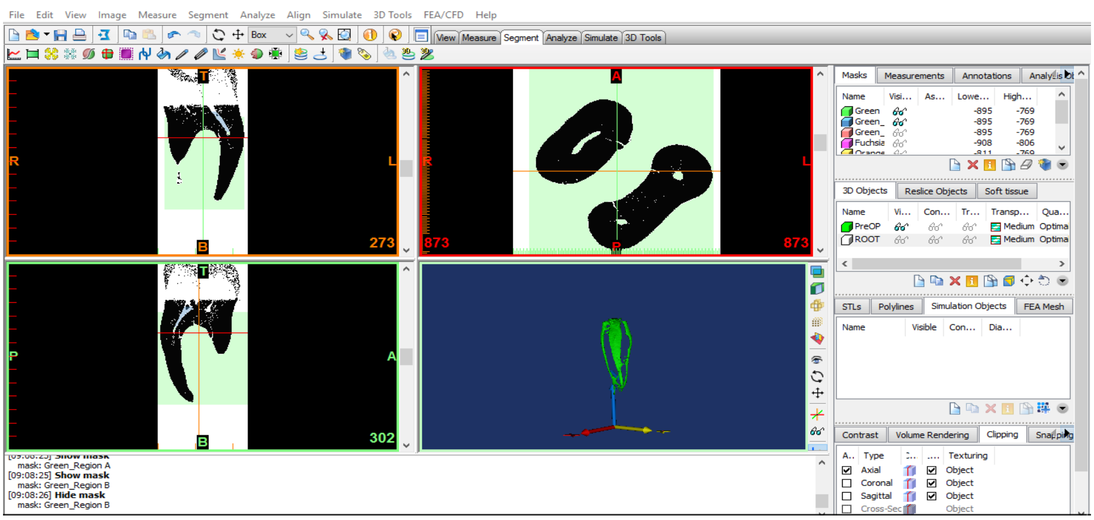


Figure 22: Showing the Materialise mimic software interface.

The three-dimensional reconstructed images were transferred to another software as binary STL files; called 3Matic *(Version 11.0*) shown in Figure 23.

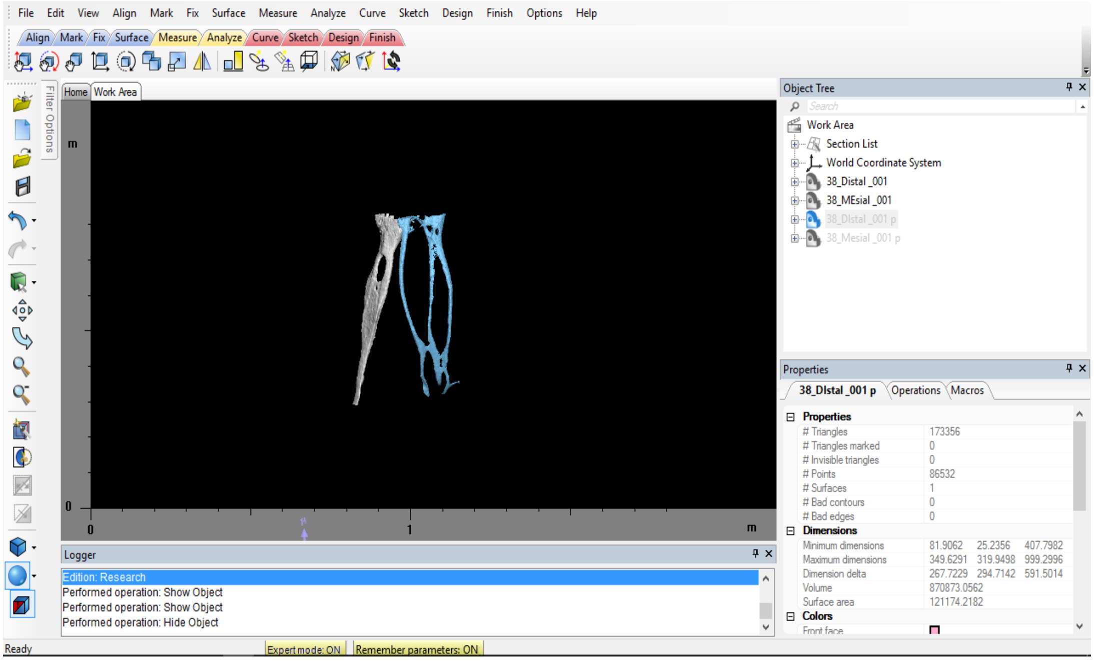


Figure 23: showing the Materialise 3-matic software interface

The 3-matic manipulated the three-dimensional images for superimposing, visualising, and creating comparison analysis for the pre-preparation and post-preparation images. Utilising manual and automated tools and an iterative algorithm; helped to achieve accurate positioning of the images. The software managed to achieve error in distance less than 2 microns.

Comparison analysis tool was used to identify the changes between the preoperative and postoperative images by running different algorithms to detect the different static and dynamic voxels. Presentation of the analysis was presented by a histogram, which showed different percentages of different areas prepared inside the root canal space, and expressed by different colours and values, an example is shown in Figure 24.

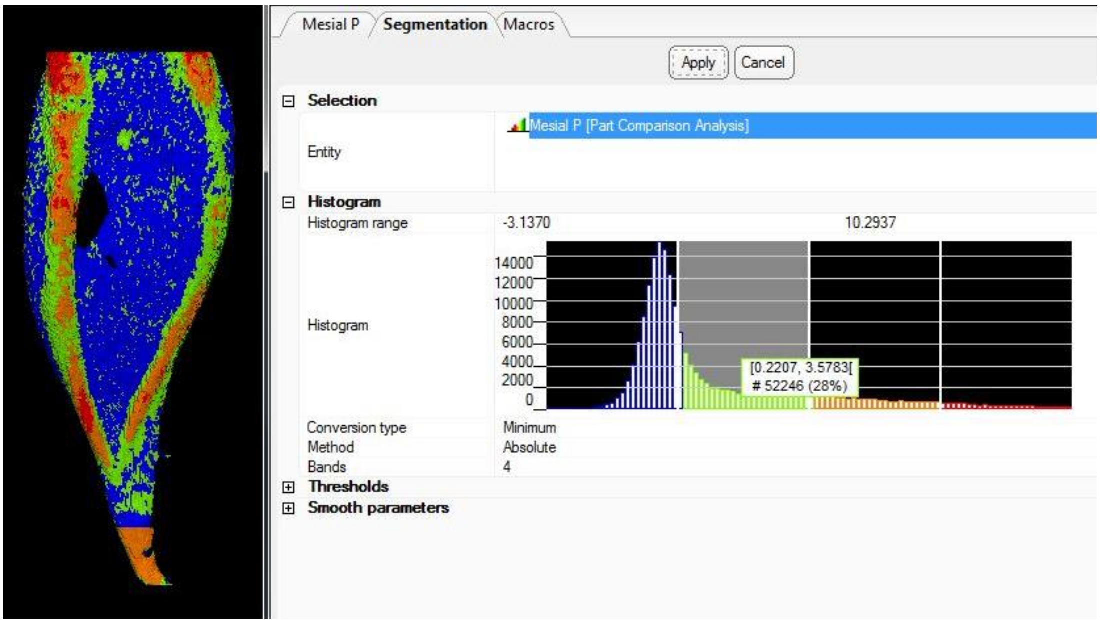


Figure 24: Illustrates the histogram showing different colours and percentages of static and dynamic voxels.

5.4.4 Statistical analysis:

The raw data was collected and entered in Microsoft excel 2013 and then transferred to SPSS statistics 24 for statistical analysis. Descriptive statistics was undertaken to represent the mean and standard deviation of the data. A univariate analysis tests was applied to the data to check if the difference in percentage of instrumentation, difference in volume of total canal space and in coronal segment of root canal space between preparations done by XPS and PTN is significant. Another univariate analysis test was applied to check if the difference of instrumentation percentage achieved by XPF file post both file systems XPS and PTN is significant.

5.5 Results:

Figure 25 showed examples of images for the pre-operative scans, post-operative scans and the comparison analysis of the canal walls instrumentation.

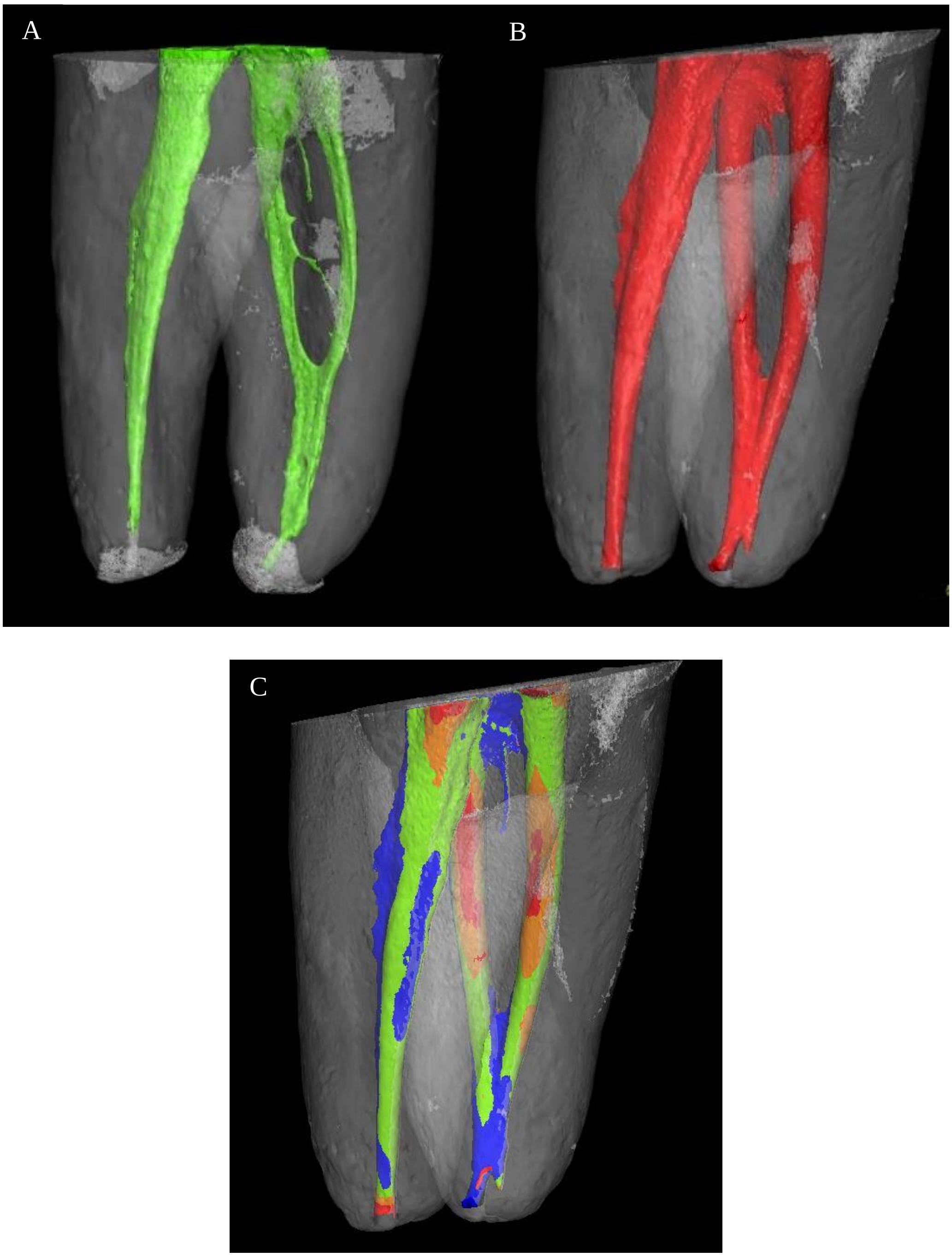


Figure 25: A) Canal space pre-preparation (Green), (B) Canal space post-preparation (Red) and (C) Canal space comparison analysis of pre & post preparation (multiple colours illustrates areas of canal space preparations with different depth in dentine)

The total number of roots, which were available for analysis, were 46 for group 1 XPS and 46 for group 2 PTN. The two roots in group 1 (mesial and distal) were excluded due to an error which occurred during the scanning. The two roots in group 2 (mesial roots) were excluded due to instrument fracture during mechanical preparation.

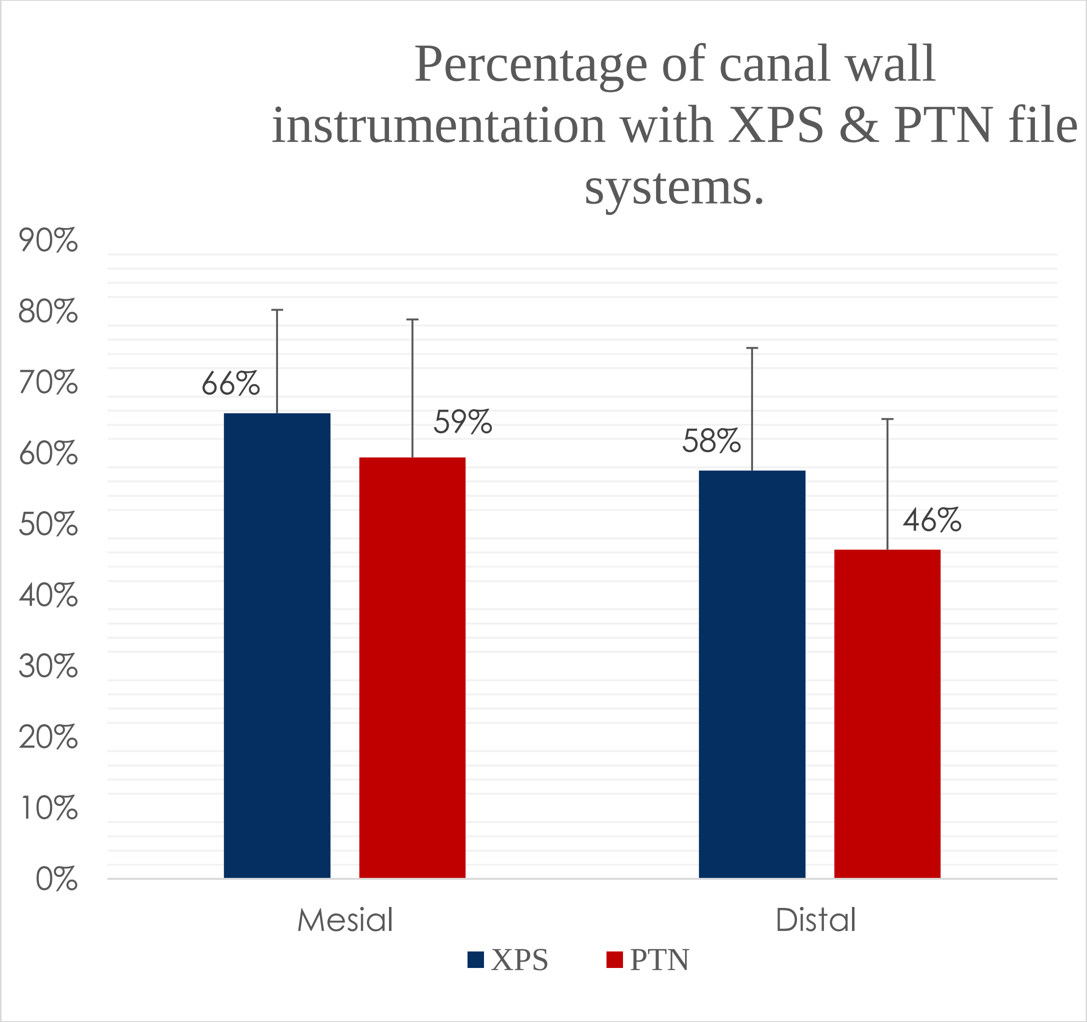


Figure 26: Percentage of canal wall instrumentation in mesial and distal roots with XP-endo Shaper and ProTaper Next.

Figure 26 showed a graph representing the means and standard deviation for each file system in mesial and distal roots. The XPS file system showed higher percentage mean of root canal wall instrumentation in both mesial and distal roots compared to the PTN file system. The mean percentage of canal wall instrumentation, in mesial roots being 66% for XPS and 59%

for PTN. In the distal root recorded a mean percentage of 58% for XPS compared with 46% for PTN.

Univariate Analysis: percentage of instrumentation with XPS & PTN			
Factors	**df**	**F**	**Significance Value**
File system	1	9.743	0.003
Canal type	1	1.224	0.275
Pre-op Vol.	63	16.388	0.000

Table 6 : Univariate analysis of Percentage of instrumentation, showing the influence of different variables on the percentage of instrumentation.

Table 6 showed the effect of different factors such as file system, canal type, and pre-operative volume on percentage of instrumentation of both file systems In univariate analysis the file system and pre-operative volume variables showed a statistically significant effect on the percentage of canal wall instrumentation of ($p<0.003$) and ($p<.000$) respectively. In addition, the difference in canal wall percentage between the two file systems was statistically significant with p value of <0.003 as using the univariate analysis. The P value comes from a linear model adjusting for the pre-operative volume and canal type.

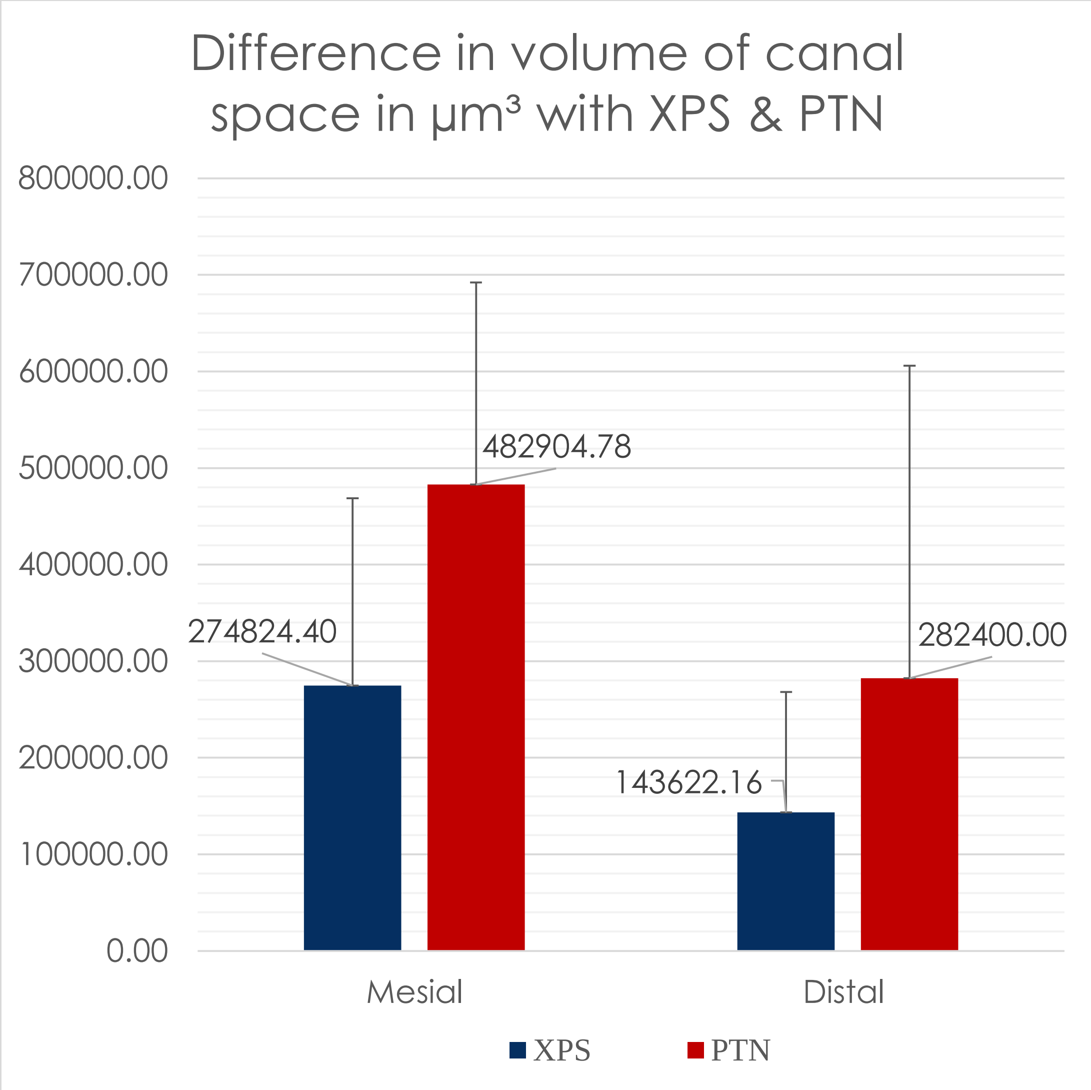


Figure 27: Difference in volume in mesial and distal roots with XP-endo Shaper and ProTaper Next.

Figure 27 showed a graph representing the means and standard deviations of the difference in volume for each file system in mesial and distal roots. For both file systems the mesial roots prepared XPS showed much lower difference in volume between the pre-operative and post-operative canal space compared to the PTN. In the distal roots, the difference in volume of root canal space with the PTN was nearly double that of the XPS.

Univariate Analysis: Difference in volume with XPS & PTN			
Factors	**df**	**F**	**Significance Value**
File system	1	4.657	0.037
Canal type	1	4.432	0.042
Pre-op Vol.	63	0.553	0.461

Table 7: Univariate analysis: Difference in volume, showing influence of different variables on the the difference in volume with XPS & PTN.

Table 7 showed the effect of different factors such as file system, canal type, and pre-operative volume on the difference in volume in mesial and distal roots, with XPS and PTN file systems. The file system and canal type showed to have a significant effect on the difference in volume of root canal space between the pre-operative and post-operative volume with p values of <0.037 and <0.042 respectively. The difference in volume between the two file systems was statistically significant with value of $p<0.037$ as reported from the general linear model adjusting for the canal type and the pre-operative volume.

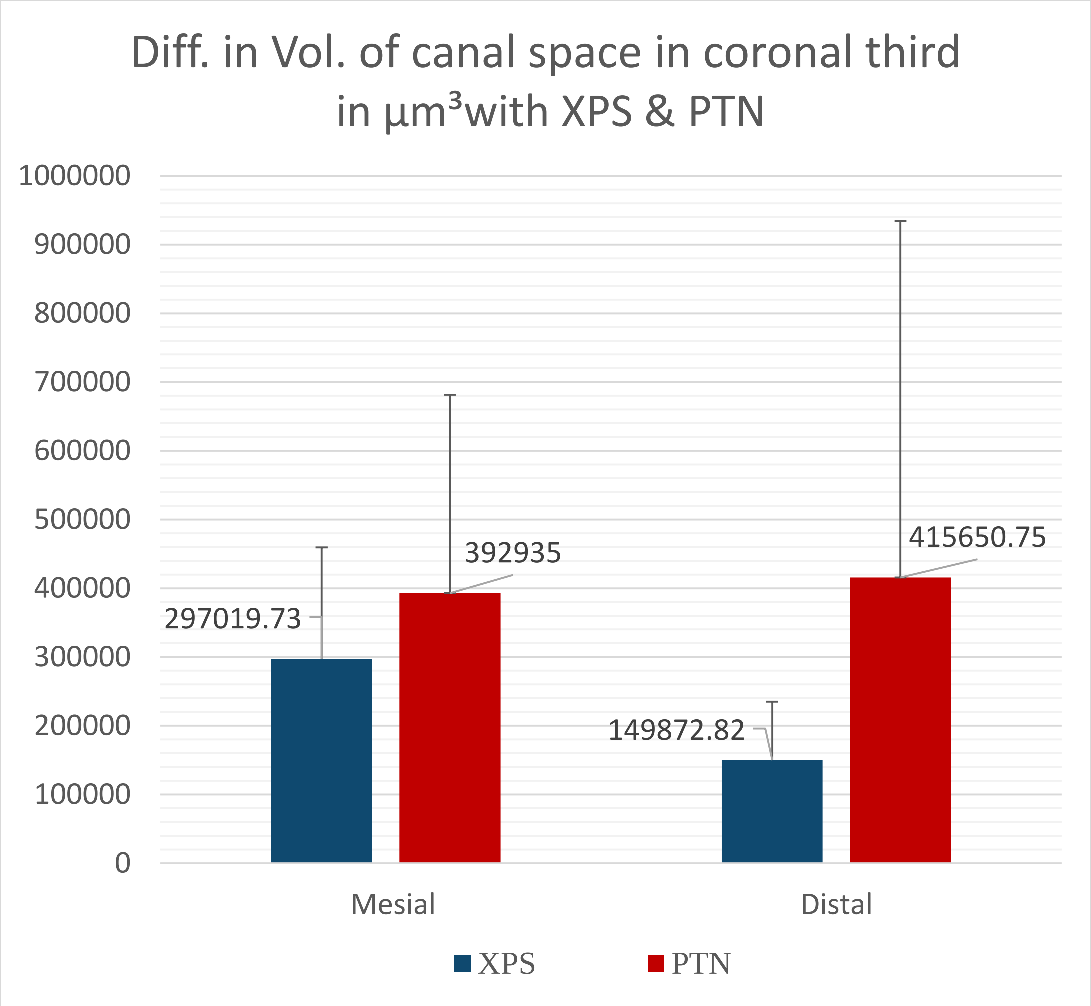


Figure 28: Difference in volume in coronal third in mesial and distal roots with XP-endo Shaper and ProTaper Next.

Figure 28 shows a graph representing the means and standard deviations of the difference in volume in coronal third for each file system in mesial and distal roots. In the mesial roots, the XPS showed lower difference in volume between the pre-operative and post-operative coronal canal space compared to the PTN. In the distal roots, the difference in volume of the coronal third of root canal space with the PTN was nearly three times that of the XPS.

Univariate Analysis: Difference in volume in coronal third with XPS & PTN			
Factors	**df**	**F**	**Significance Value**
File system	1	2.072	0.158
Canal type	1	0.072	0.792
Pre-op Vol.	1	1.561	0.219

Table 8: Univariate analysis: Difference in volume in coronal third, showing influence of different variables on volume of the coronal third with XPS and PTN

Table 8 showed the effect of different factors such as file system, canal type, and pre-operative volume on the difference in volume in coronal third in mesial and distal roots, with XPS and PTN file systems. The analysis showed that none of the factors had a significant effect on the difference in volume in the coronal third. In addition, it showed no statistical significant difference between the two file systems or between the mesial and distal canals.

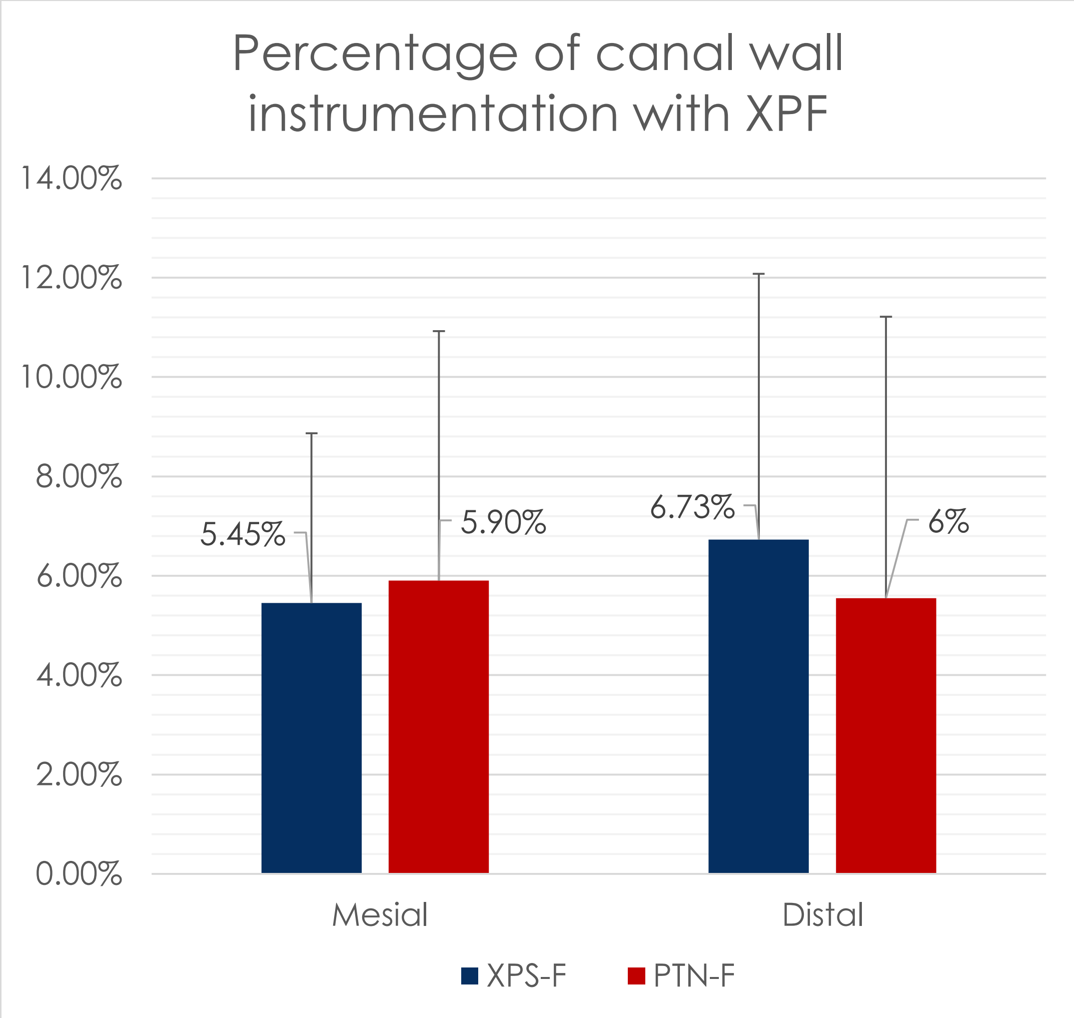


Figure 29: Percentage of canal wall instrumentation with XPF after XPS and PTN file systems in mesial and distal roots.

Figure 29 shows a graph representing the means and standard deviation of percentage of canal wall instrumentation with XPF after each file system in mesial and distal roots. The percentage of canal wall instrumentation with the XPF was similar after both file systems in the mesial and distal roots. The XPF showed slightly higher mean percentage of instrumentation in distal root compared to the mesial root after both file systems.

Univariate Analysis: percentage of instr. with XPF			
Factors	**df**	**F**	**Significance Value**
File system	1	0.294	0.590
Canal type	1	0.310	0.581
Pre-op Vol.	1	0.851	0.362

Table 9: Univariate analysis: Percentage of instrumentation with XPF file, showing influence of different variables on the percentage of instrumentation with XPF.

Table 9 showed the effect of different factors such as file system, canal type, and pre-operative volume on the percentage of instrumentation of canal walls with the XPF file. The three factors did not have any significant effect on the percentage of instrumentation with the XPF file. The different percentage of instrumentation with the XPF file after the XPS or PTN did not show any statistical significance.

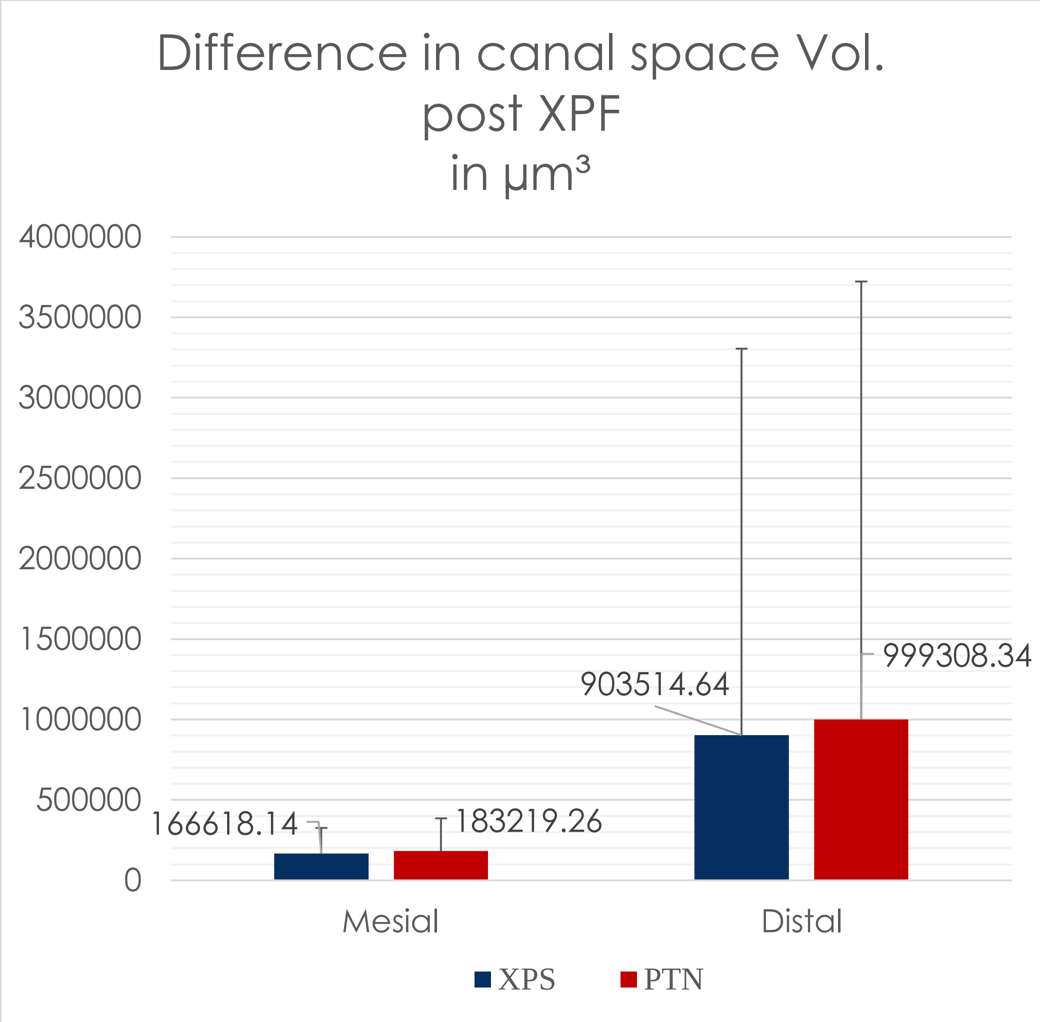


Figure 30: Difference in volume in mesial and distal roots after instrumentation with XP-endo finisher post XP-endo Shaper and ProTaper Next.

Figure 30 shows a graph representing the means and standard deviation difference in volume happened with XPF after each file system in the mesial and distal roots. The difference in volume in the distal roots was higher than the mesial roots in both file systems. The difference in volume in the mesial roots and distal roots was close in value for both XPS and PTN.

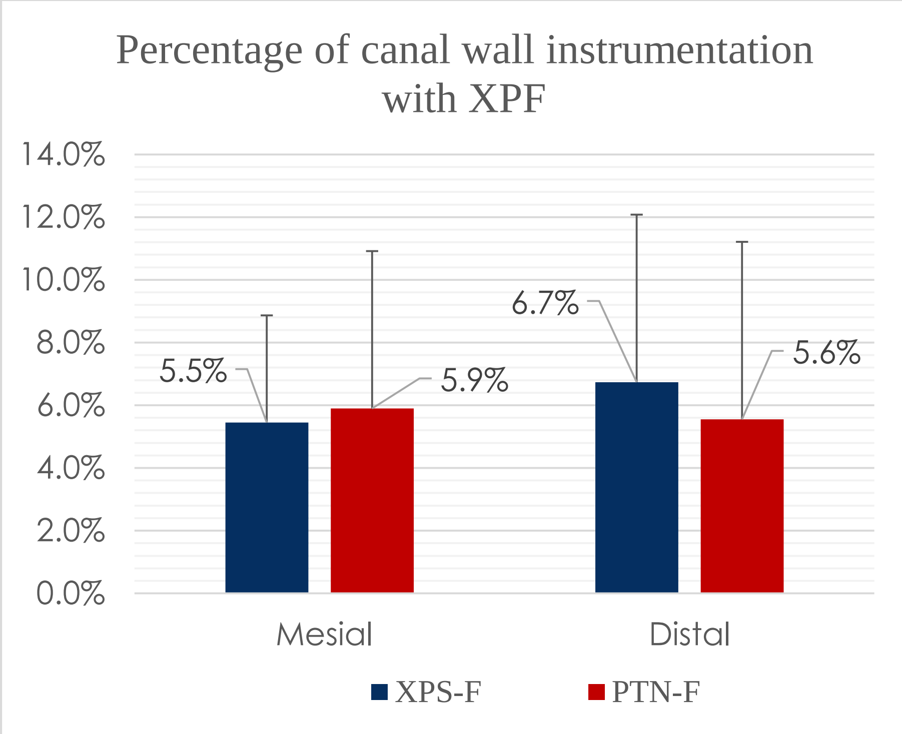


Figure 31: Percentage of canal wall instrumentation with XPF file post XPS and PTN.

Figure 31 showed the means and standard deviations of percentage of canal wall instrumentation of XPF file post both file systems XPS and PTN The percentage of instrumentation combining the XPS file system and the XPF file was 71.5 % for mesial roots compared with 64.9% combining the PTN file system and XPF file. In distal canals, the percentage of instrumentation with combining the XPS file system and XPF file is 64.7 %, while the percentage with combining the PTN file system and XPF file is 51.6%.

5.6 Discussion:

For several decades, the main problem with root canal treatment is the high variation and complexity of the root canal anatomy (Peters, 2004, Vertucci, 2005). This complexity had a significant influence on the mechanical instrumentation of the root canal space, endodontic files were unable to instrument some areas and the cleaning is mainly dependent on the chemical aspect either by intra-canal medication or irrigants with the aid of ultrasonic or lasers (Hülsmann *et al.*, 2005a). Some concepts are using rotary NiTi file systems designed with large tapers to create more space for the irrigants to enhance irrigant flow inside canals and achieve better chemical cleaning. In addition, creating larger apical size preparations can result in reduction in bacterial load and enhance irrigant flow. Most of these preparations are not conservative, due to excess dentine removal resulting in dentinal cracks and weakened tooth structure, which can affect the long-term survival of the tooth (Bier *et al.*, 2009).

This study investigated the efficacy of mechanical instrumentation of canal walls and geometrical changes using µCT. Previous reported methods of assessing the efficacy of mechanical preparation of root canal spaces were *in-vitro studies* using cleared extracted teeth, silicone impressions of the canal space, teeth horizontal sectioning, vertical splitting, muffle system and superimposition of radiographs (Barthel *et al.*, 1999, Bramante *et al.*, 1987, Hülsmann *et al.*, 2005b, Nagy *et al.*, 1997, Schneider, 1971, Weine *et al.*, 1975). All these methods were inferior to the micro CT used in this study. Micro-CT proved to be beneficial and highly accurate to use for this type of investigations and analysis (Fernandes *et al*., 2016, Plotino *et al.*, 2006, Swain and Xue, 2009). In this study micro CT, showed the benefit of being non-destructive, and allowing the samples to be analysed several times on different occasions after multiple manipulations.

This study highlighted the efficacy, shaping, expansion abilities and conservative preparation of the recently introduced instrument (XPS). The file represent a new generation of NiTi rotary files that can expand beyond its core. The available standard NiTi rotary files doesn't not show the same properties despite of their flexibility and alloy properties. In this study the PTN NiTi rotary file was chosen for comparison, because of its wide use, off centred design and asymmetrical rotary motion to improve shaping efficiency and more importantly its ability to respect the root canal anatomy and conserve dentine (Gagliardi *et al.*, 2015, Wu *et al.*, 2015).

The findings of the study showed lower efficacy of canal wall instrumentation using PTN compared with the XPS. The results showed that XPS achieved higher percentage of mechanical instrumentation of the root canal walls compared to the PTN with statistically significant difference. Based on these findings the null hypothesis suggesting no difference in percentage of root canal wall instrumentation was rejected. The percentages achieved with the XPS are comparable to the percentages achieved with other types of engine drive file systems before in the literature (De-Deus *et al.*, 2015, Paqué and Peters, 2011, Peters and Paqué, 2011). Previous micro CT studies suggested that 45-65% of the canal walls instrumented (Peters *et al.*, 2001b) which was lower than the results obtained in this study. A recent study published in September 2017 by Azim *et al.* showed a similar percentage of root canal instrumentation to this study and demonstrated that the XPS can expand beyond its core and adapt to root canal anatomy. Although the results are comparable to this study, the analysis by Azim *et al*. was done on lower anterior teeth with oval shaped canals and the scanning resolution was 25 microns which is lower resolution compared to this study (Azim *et al.*, 2017). The percentage of instrumentation found by Azim *et al* shows similar percentage of instrumentation in the same canal anatomy, which is the oval shape in the lower mandibular anterior teeth and the distal roots of the mandibular molars. However, in this study the mesial roots showed higher percentage of instrumentation compared with distal roots and the results from Azim *et al.* study.

In this study the XPS and PTN were affected by the preoperative volume of the root canal space. The XPS performed better in tighter canal spaces like the mesial roots compared to distal roots. XPS was also more conservative in removing root dentine compared to PTN with statistically significant difference in both mesial and distal roots, hence the null hypothesis suggesting no difference in dentine preservation between the two file systems was rejected. In the coronal third of the canal, although PTN removed more dentine compared with XPS, however this was not statistically significant. This agrees with the null hypothesis suggesting there in no difference in the amount of dentine removed in the coronal segment of the root canal between the two file systems. Although there was no statistical significance detected, this was likely due to the study being underpowered as the sample size calculation was computed for different outcome measure. Increasing the sample size if the study to be repeated in the future, might show statistical significance between the two file systems XPS and PTN, however that will have a greatly increase the time for scanning and analysis. The difference in taper created by the 2 file systems (6% for PTN, and 4% for XPS) may be the reason for this difference in dentine preservation. Clinically, the coronal third of the root is a critical area that affects the strength of the tooth structure, so trying to remove less dentine in this area without compromising the mechanical instrumentation efficacy is preferable.

Despite conservative nature of XPS, it still achieves high instrumentation efficacy, which gives a better chance for the irrigant to flow, clean and at the same time leave the tooth with a stronger structure. In addition a study conducted recently by Bayram *et al.* showed that the XPS did not induce any dentinal micro-crack propagation during instrumentation of the root canal system (Bayram *et al.*, 2017). This is also explained by minimal stress induced by the files outer surface on the canal walls. More root canal space during the instrumentation process can allow debris to escape the canal which results in decreased resistance on the canal walls. The XPS was found to have a limited expansion beyond its core, which was demonstrated with lower percentage of root canal walls instrumentation in wider and oval shaped canals found in distal roots. The file achieves maximum expansion when it undergoes transformation from martensitic to austenitic phase at approx. 35-37°C. The transformation temperature was maintained during the experiment, however in reality the file may not reach the required temperature as the dentine is not a good thermal conductor. In addition dental dam isolation and the irrigant temperature can also influence the surrounding temperature. The deficiency of XP file expansion may be helped by a higher speed of rotation than the 800 RPM recommended by the manufacturer to help achieve a better horizontal expansion.

XPF was found to have a minimal percentage of instrumentation and dentine removal after both file systems (XPS and PTN) with no statistically significant difference in both roots. Therefore, the null hypothesis was accepted. The XPF appeared to have a better instrumentation efficacy in wide canals, as seen in distal roots compared with canals in mesial roots. That can be interpreted that the file has a good ability of expanding beyond its core when enough space is present. In the author's opinion, the increase in efficacy and improved expansion might be related to the design of the file with high flexibility (0% taper) and the high file rotation speed (800-1000 RPM).

The study design (randomised single blinded), standardising the molars, considering different variability in groups and applying stratified randomisation, aimed to attempt to minimise any source of bias on the results. Despite using stratified randomisation, there was still some imbalance in the preoperative volume between the two groups. This imbalance resulted in the use of difference in volume between the pre-operative and post-operative images for the statistical analysis, instead of the final volume, to minimise any bias.

Mandibular molars were chosen because of the presence of complex anatomy, such as isthmuses in mesial root and oval shape canal in distal root. The isthmuses and the oval shape canals were considered a challenge for mechanical instrumentation. Pre-scanning with µCT was done to assess canal anatomy in mandibular molars which normally have high variation of root canal anatomy (Vertucci, 2005) in order to balance the groups.

In this study a single operator carried out all the preparation procedures to reduce the variation that might occur between different operators, however, that can still result in some bias, due to intra-operator variability during the procedure, which might influence the outcome. The intra-operator variability effect can be tested and rectified by applying intra-operator variability test, which will show the level of preparation consistency between samples. This should be considered if the study design is conducted in the future.The preparation with XPS and XPF was carried out in a water bath of 37 degrees C to avoid any effect on the phase transition of the alloy. Although the other group (PTN) was not prepared in the same water bath, the teeth were still prepared with irrigation similar to the other group.

Custom made holders for the samples were used in micro CT scan to help avoiding inaccuracies during superimposition of the pre and post-preparation images. The Materialise software package was chosen for its high accuracy in segmentation and three dimensional model reconstruction showed by independent studies (Gelaude *et al.*, 2008, Jamali *et al.*, 2007, Moerenhout *et al.*, 2008). Although high accuracy of the software have been demonstrated, it is unknown whether the results will still be similar if a different software was used or a different operator used the software for analysis. A combination of manual and automated tools were used for the superimposition of the images to minimise errors and ensure accuracy of the results. Despite measures used to minimise the bias, there is still a possibility of inaccuracy, due to the limitations of µCT scanning and the potential for multiple sources of errors throughout the procedure starting with the scanning of the sample to the comparison analysis.

The available evidence in the literature showed that the mechanical instrumentation of root canal walls helps to disrupt any biofilm present. Whether the improvement in percentage of root canal wall instrumentation will have a significant effect on the clinical outcome remains to be verified. However some researchers and clinicians have argued the importance of achieving a higher percentage of canal wall contact with instruments, in order to improve the success rates of root canal treatment (Ng *et al.*, 2007).

The need for further research is necessary in order to investigate the effect of the instrumentation efficacy on the irrigant flow inside the root canal space. In addition, there is also a need to investigate the effect on bacterial load and clinical outcome of root canal treatment.

5.7 Conclusion:

Within the limitation of the study, the XPS file system achieved higher percentage of root canal wall instrumentation compared with PTN file system. The XPS showed more conservative root canal preparation compared with PTN.

XPF file used as a finisher file after both rotary file systems XPS and PTN improved the percentage of root canal wall instrumentation without a significant effect on further loss of the root dentine.

Chapter 6: Clinical implications & future research

6.1 Clinical implications

The outcome of the first study showed a significant difference between the number of procedural errors between both file systems ProTaper Universal and ProTaper in the hands of novice users (Undergraduate students). In addition the ProTaper Next appeared to be more time and cost effective. Novice users of the ProTaper Next file system are more likely to have a higher number of successful root canal treatments and this will improve the operator confidence in endodontic instrumentation, especially if the operator is in early stages of training.

The outcome of the second study revealed the ability of root canal instrumentation of a newly introduced file system to the market to instrument root canals. The XP-endo Shaper was effective in mechanical instrumentation of root canal walls and also conserved root canal dentine in comparison to the ProTaper Next rotary system. In addition finishing the root canal preparation using XP-endo Finisher file improves the percentage of canal wall instrumentation, without further compromising the root dentine. These findings will be reflected clinically in better mechanical instrumentation of the root canal system without adversely affecting the strength of the root, theoretically this should result in better outcomes for root canal preparation and long-term tooth survival.

6.2 Future research

- Investigation of recent file systems such as, ProTaper gold, Wave one gold, and Reciproc blue for their technical outcomes, procedural errors and time efficiency in the hands of novice operators. Using human extracted teeth and micro-computed tomography technology will help to avoid the draw backs of using simulated canals in resin blocks. The outcome of these investigations should help in informing and applying modifications to the preclinical training protocol for Dental Students. In addition it should help in recommendation of what file system is more safe and efficient for newly qualified dental practitioners.

- Further investigations should be conducted regarding the XP-endo Shaper file as a continuation phase to this study and based on the findings.

- The 1st phase will be to investigate the irrigant flow and reachability inside dentinal tubules. This can be carried out using radiopaque irrigant or using the standard irrigant (NaOCl) mixed with a radiopaque material evaluated by micro-CT and image analysis.

  The 2nd phase is to see the effect of the mechanical instrumentation on bacterial debridement and disruption of the biofilm. That can be investigated using scanning electron microscope or laser confocal microscopy.

  The 3rd phase will be to investigate if using this file system has an effect on the clinical success in patients, by running a randomised controlled trial. The assessment should be done by cone beam CT, in order to avoid the drawbacks of two-dimensional radiographs and to verify real difference in clinical success compared to the present percentages in the literature.

6.3 Conclusions

The narrative review of the endodontic literature regarding root canal instrumentation revealed some gaps in the area of operator experience, specially inexperienced users and the effect of their skills on the root canal instrumentation and the incidence of procedural errors. In addition there was a lack of evidence regarding recently introduced rotary NiTi file system and their ability to instrument root canals.

The use of ProTaper Next file system over ProTaper Universal file system by novice users; (Undergraduate dental students in preclinical training or clinical environments or newly graduated general dental practitioners in a clinical environment), can result in fewer procedural errors, improved time efficiency and better technical outcome of root canal preparation.

The use of recently introduced XPS NiTi files produced a higher percentage of root canal wall instrumentation compared with PTN, whilst also preserving the root dentine. The use of XPF NiTi finisher file after XPS or PTN showed further improvements in root canal instrumentation percentage without significant detrimental effects on dentine preservation.

References

ALAPATI, S. B., BRANTLEY, W. A., IIJIMA, M., CLARK, W. A. T., KOVARIK, L., BUIE, C., LIU, J. & BEN JOHNSON, W. 2009. Metallurgical Characterization of a New Nickel-Titanium Wire for Rotary Endodontic Instruments. *Journal of Endodontics,* 35**,** 1589-1593.

ANDREASEN, G. F. & MORROW, R. E. 1978. Laboratory and clinical analyses of nitinol wire. *American Journal of Orthodontics,* 73**,** 142-151.

AZIM, A. A., AKSEL, H., ZHUANG, T., MASHTARE, T., BABU, J. P. & HUANG, G. T. J. 2016. Efficacy of 4 Irrigation Protocols in Killing Bacteria Colonized in Dentinal Tubules Examined by a Novel Confocal Laser Scanning Microscope Analysis. *Journal of Endodontics,* 42**,** 928-934.

AZIM, A. A., PIASECKI, L., DA SILVA NETO, U. X., CRUZ, A. T. G. & AZIM, K. A. 2017. XP Shaper, A Novel Adaptive Core Rotary Instrument: Micro–computed Tomographic Analysis of Its Shaping Abilities. *Journal of Endodontics,* 43**,** 1532-1538.

BALANI, P., NIAZI, F. & RASHID, H. 2015. A brief review of the methods used to determine the curvature of root canals. *Journal of Restorative Dentistry,* 3**,** 57-63.

BAO, P., SHEN, Y., LIN, J. & HAAPASALO, M. 2017. In Vitro Efficacy of XP-endo Finisher with 2 Different Protocols on Biofilm Removal from Apical Root Canals. *Journal of Endodontics,* 43**,** 321-325.

BARTHEL, C. R., GRUBER, S. & ROULET, J.-F. 1999. A new method to assess the results of instrumentation techniques in the root canal. *Journal of Endodontics,* 25**,** 535-538.

BAUGH, D. & WALLACE, J. 2005. The Role of Apical Instrumentation in Root Canal Treatment: A Review of the Literature. *Journal of Endodontics,* 31**,** 333-340.

BAUMANN, M. A. & ROTH, A. 1999. Effect of experience on quality of canal preparation with rotary nickel-titanium files. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology, and Endodontology,* 88**,** 714-718.

BAYRAM, H. M., BAYRAM, E., OCAK, M., UYGUN, A. D. & CELIK, H. H. 2017. Effect of ProTaper Gold, Self-Adjusting File, and XP-endo Shaper Instruments on Dentinal Microcrack Formation: A Micro–computed Tomographic Study. *Journal of Endodontics,* 43**,** 1166-1169.

BERGMANS, L., CLEYNENBREUGEL, J., BEULLENS, M., WEVERS, M., MEERBEEK, B. & LAMBRECHTS, P. 2003. Progressive versus constant tapered shaft design using NiTi rotary instruments. *Int Endod J,* 36.

BIER, C. A. S., SHEMESH, H., TANOMARU-FILHO, M., WESSELINK, P. R. & WU, M.-K. 2009. The Ability of Different Nickel-Titanium Rotary Instruments To Induce Dentinal Damage During Canal Preparation. *Journal of Endodontics,* 35**,** 236-238.

BOUTSIOUKIS, C., GOGOS, C., VERHAAGEN, B., VERSLUIS, M., KASTRINAKIS, E. & VAN DER SLUIS, L. W. M. 2010. The effect of root canal taper on the irrigant flow: evaluation using an unsteady Computational Fluid Dynamics model. *International Endodontic Journal,* 43**,** 909-916.

BRAMANTE, C. M., BERBERT, A. & BORGES, R. P. 1987. A methodology for evaluation of root canal instrumentation. *Journal of Endodontics,* 13**,** 243-245.

BRUKER. 2013. *Skyscan micro Ct scanner* [Online]. Available: http://www.bruker-microct.com/products/1272.htm [Accessed].

BRYANT, THOMPSON, AL, O. & DUMMER 1998. Shaping ability of Profile rotary nickel-titanium instruments with ISO sized tips in simulated root canals: Part 1. *International Endodontic Journal,* 31**,** 275-281.

BUEHLER, W. J., GILFRICH, J. V. & WILEY, R. C. 1963. Effect of Low-Temperature Phase Changes on the Mechanical Properties of Alloys near Composition TiNi. *Journal of Applied Physics,* 34**,** 1475-1477.

BÜRKLEIN, S., HINSCHITZA, K., DAMMASCHKE, T. & SCHÄFER, E. 2012. Shaping ability and cleaning effectiveness of two single-file systems in severely curved root canals of extracted teeth: Reciproc and WaveOne versus Mtwo and ProTaper. *International Endodontic Journal,* 45**,** 449-461.

CAMPS, J. J. & PERTOL, W. J. 1994. Relationship between file size and stiffness of stainless steel instruments. *Dental Traumatology,* 10**,** 260-263.

CAPAR, I. D., ARSLAN, H., AKCAY, M. & ERTAS, H. 2014a. An In Vitro Comparison of Apically Extruded Debris and Instrumentation Times with ProTaper Universal, ProTaper Next, Twisted File Adaptive, and HyFlex Instruments. *Journal of Endodontics,* 40**,** 1638-1641.

CAPAR, I. D., ARSLAN, H., AKCAY, M. & UYSAL, B. 2014b. Effects of ProTaper Universal, ProTaper Next, and HyFlex Instruments on Crack Formation in Dentin. *Journal of Endodontics,* 40**,** 1482-1484.

CAPAR, I. D., ERTAS, H., OK, E., ARSLAN, H. & ERTAS, E. T. 2014c. Comparative study of different novel nickel-titanium rotary systems for root canal preparation in severely curved root canals. *J Endod,* 40.

CARD, S. J., SIGURDSSON, A., ØRSTAVIK, D. & TROPE, M. 2002. The Effectiveness of Increased Apical Enlargement in Reducing Intracanal Bacteria. *Journal of Endodontics,* 28**,** 779-783.

CLEM, W. H. 1969. Endodontics: the adolescent patient. *Dent Clin North Am,* 13**,** 482-93.

COHEN, S. & HARGREAVES, K. M. 2006. *Pathways of the pulp,* St. Louis : London : 2006, 9th ed.

DAVIS, G. R. & ELLIOTT, J. C. 2006. Artefacts in X-ray microtomography of materials. *Materials Science and Technology,* 22**,** 1011-1018.

DE-DEUS, G., ARRUDA, T. E. P., SOUZA, E. M., NEVES, A., MAGALHÃES, K., THUANNE, E. & FIDEL, R. A. S. 2013. The ability of the Reciproc R25 instrument to reach the full root canal working length without a glide path. *International Endodontic Journal,* 46**,** 993-998.

DE-DEUS, G., BELLADONNA, F. G., SILVA, E. J. N. L., MARINS, J. R., SOUZA, E. M., PEREZ, R., LOPES, R. T., VERSIANI, M. A., PACIORNIK, S. & NEVES, A. D. A. 2015.

Micro-CT Evaluation of Non-instrumented Canal Areas with Different Enlargements Performed by NiTi Systems. *Brazilian Dental Journal,* 26**,** 624-629.

DE-DEUS, G. & GARCIA-FILHO, P. 2009. Influence of the NiTi rotary system on the debridement quality of the root canal space. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology, and Endodontology,* 108**,** e71-e76.

DE-DEUS, G., SILVA, E. J. N. L., VIEIRA, V. T. L., BELLADONNA, F. G., ELIAS, C. N., PLOTINO, G. & GRANDE, N. M. 2017. Blue Thermomechanical Treatment Optimizes Fatigue Resistance and Flexibility of the Reciproc Files. *Journal of Endodontics,* 43**,** 462-466.

DENTSPLY. 2007. *M-wire NiTi by DENTSPLY* [Online]. Available: http://mwireniti.com/ [Accessed].

DENTSPLY. 2015. *TRUShape 3D Conforming File* [Online]. Available: https://www.dentsply.com/content/dam/dentsply/pim/manufacturer/Endodontics/Glide_Path__Shaping/Rotary__Reciprocating_Files/3D_Conforming/TRUShape_3D_Conforming_Files/TRUShape-3D-Conforming-Files-Brochure-2vkhexu-en-1504.pdf [Accessed].

DHINGRA, A., BANERJEE, S., YADAV, V. & AGGARWAL, N. 2014. Canal Shaping with ProTaper Next and ProTaper Universal: A Comparative Study. *Annals of Dental Research,* 4**,** 6-14.

DUMMER, P. M. H. 1991. Comparison of undergraduate endodontic teaching programmes in the United Kingdom and in some dental schools in Europe and the United States. *International Endodontic Journal,* 24**,** 169-177.

DUMMER, P. M. H., ALODEH, M. H. A. & AL-OMARI, M. A. O. 1991. A method for the construction of simulated root canals in clear resin blocks. *International Endodontic Journal*, 24**,** 63-66.

ELEFTHERIADIS, G. I. & LAMBRIANIDIS, T. P. 2005. Technical quality of root canal treatment and detection of iatrogenic errors in an undergraduate dental clinic. *International Endodontic Journal*, 38**,** 725-734.

ELIZABETH M, S. 2005. Hand instrumentation in root canal preparation. *Endodontic Topics*, 10**,** 163-167.

ELNAGHY, A. M. 2014. Cyclic fatigue resistance of ProTaper Next nickel-titanium rotary files. *Int Endod J*, 47.

ELNAGHY, A. M. & ELSAKA, S. E. 2017. Torsional resistance of XP-endo Shaper at body temperature compared with several nickel-titanium rotary instruments. *International Endodontic Journal***,** n/a-n/a.

ELNAGHY, A. M., MANDORAH, A. & ELSAKA, S. E. 2017. Effectiveness of XP-endo Finisher, EndoActivator, and File agitation on debris and smear layer removal in curved root canals: a comparative study. *Odontology*, 105**,** 178-183.

ESE 2006. Quality guidelines for endodontic treatment: consensus report of the European Society of Endodontology. *International Endodontic Journal*, 39**,** 921-930.

FERNANDES, J. S., APPOLONI, C. R. & FERNANDES, C. P. 2016. Accuracy evaluation of an X-ray microtomography system. *Micron*, 85**,** 34-38.

FKG XP endo Finisher.

FKG. 2015. *XP-Endo finisher file* [Online]. Available: http://www.fkg.ch/sites/default/files/fkg_xp_endo_brochure_en_vb.pdf [Accessed].

FKG 2017. XP-endo Shaper protocol.

FOURIE, Z., DAMSTRA, J., SCHEPERS, R. H., GERRITS, P. O. & REN, Y. 2012. Segmentation process significantly influences the accuracy of 3D surface models derived from cone beam computed tomography. *European Journal of Radiology,* 81**,** e524-e530.

FRIEDMAN, S., ABITBOL, S. & LAWRENCE, H. P. 2003. Treatment Outcome in Endodontics: The Toronto Study. Phase 1: Initial Treatment. *Journal of Endodontics,* 29**,** 787-793.

GAGLIARDI, J., VERSIANI, M. A., DE SOUSA-NETO, M. D., PLAZAS-GARZON, A. & BASRANI, B. 2015. Evaluation of the Shaping Characteristics of ProTaper Gold, ProTaper NEXT, and ProTaper Universal in Curved Canals. *Journal of Endodontics,* 41**,** 1718-1724.

GAMBILL, J. M., ALDER, M. & DEL RIO, C. E. 1996. Comparison of nickel-titanium and stainless steel hand-file instrumentation using computed tomography. *Journal of Endodontics,* 22**,** 369-375.

GARIP, Y. & GÜNDAY, M. 2001. The use of computed tomography when comparing nickel–titanium and stainless steel files during preparation of simulated curved canals. *International Endodontic Journal,* 34**,** 452-457.

GELAUDE, F., VANDER SLOTEN, J. & LAUWERS, B. 2008. Accuracy assessment of CT-based outer surface femur meshes. *Computer Aided Surgery,* 13**,** 188-199.

GIULIANI, V., NASSO, L., PACE, R. & PAGAVINO, G. 2014. Shaping ability of WaveOne primary reciprocating files and ProTaper system used in continuous and reciprocating motion. *J Endod,* 40.

GLOSSON, C. R., HALLER, R. H., BRENT DOVE, S. & DEL RIO, C. E. 1995. A comparison of root canal preparations using Ni-Ti hand, Ni-Ti engine-driven, and K-Flex endodontic instruments. *Journal of Endodontics,* 21**,** 146-151.

GOLDBERG, M., KULKARNI, A. B., YOUNG, M. & BOSKEY, A. 2011. Dentin: Structure, Composition and Mineralization: The role of dentin ECM in dentin formation and mineralization. *Frontiers in Bioscience (Elite Edition),* 3**,** 711-735.

GÜNDAY, M., SAZAK, H. & GARIP, Y. 2005. A Comparative Study of Three Different Root Canal Curvature Measurement Techniques and Measuring the Canal Access Angle in Curved Canals. *Journal of Endodontics,* 31**,** 796-798.

GUNNAR BERGENHOLTZ , P. H.-B., CLAES REIT Nov 2009. *Chapter 1 , Textbook of Endodontology 2nd edition,* Wiley-Blackwell.

GUTMANN, J. L. & LOVDAHL, P. E. 2011. Chapter 1 - Problem Solving in the Diagnosis of Odontogenic Pain. *Problem Solving in Endodontics (Fifth Edition).* Saint Louis: Mosby.

HAAPASALO, M. & SHEN, Y. 2013. Evolution of nickel–titanium instruments: from past to future. *Endodontic Topics,* 29**,** 3-17.

HABIB, A. A., TAHA, M. I. & FARAH, E. M. 2015. Methodologies used in quality assessment of root canal preparation techniques: Review of the literature. *Journal of Taibah University Medical Sciences,* 10**,** 123-131.

HARGREAVES, K. M. 2010. *Chapter 9, Cohen's pathways of the pulp expert consult*, Mosby.

HTTP://WWW.PROTAPERNEXT.COM/DOWNLOADS/PROGLIDER-PROTAPER-NEXT-SEQUENCE-CARD-LR-0913.PDF Protaper Next sequence card.

HÜLSMANN, M., PETERS, O. A. & DUMMER, P. M. 2005a. Mechanical preparation of root canals: shaping goals, techniques and means. *Endodontic topics,* 10**,** 30-76.

HÜLSMANN, M., PETERS, O. A. & DUMMER, P. M. H. 2005b. Mechanical preparation of root canals: shaping goals, techniques and means. *Endod Top,* 10.

IDA, R. & GUTMANN, J. 1995. Importance of anatomic variables in endodontic treatment outcomes: case report. *Dental Traumatology,* 11**,** 199-203.

INGLE, J. I. 1961. A standardized endodontic technique utilizing newly designed instruments and filling materials. *Oral Surgery, Oral Medicine, Oral Pathology,* 14**,** 83-91.

JAMALI, A. A., DEUEL, C., PERREIRA, A., SALGADO, C. J., HUNTER, J. C. & STRONG, E. B. 2007. Linear and angular measurements of computer-generated models: Are they accurate, valid, and reliable? *Computer Aided Surgery,* 12**,** 278-285.

KAZEMI, R. B., STENMAN, E. & SPNGBERG, L. S. W. 1996. Machining efficiency and wear resistance of nickel-titanium endodontic files. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology, and Endodontology,* 81**,** 596-602.

KHABBAZ, M. G., PROTOGEROU, E. & DOUKA, E. 2010. Radiographic quality of root fillings performed by undergraduate students. *International Endodontic Journal,* 43**,** 499-508.

KLEVANT, F. J. & EGGINK, C. O. 1983. The effect of canal preparation on periapical disease. *Int Endod J,* 16**,** 68-75.

KOCH, K. 2002. Real world endo : Design features of rotary files and how they affect clinical performance. *Oral Health***,** 39-49.

LANDIS, E. N. & KEANE, D. T. 2010. X-ray microtomography. *Materials Characterization,* 61**,** 1305-1316.

LATURNO, S. A. L., CORCORAN, J. F. & ELLISON, R. L. 1984. An evaluation of a teaching aid in endodontics. *Journal of Endodontics,* 10**,** 507-511.

LERTCHIRAKARN, V., PALAMARA, J. E. A. & MESSER, H. H. 2003. Patterns of Vertical Root Fracture: Factors Affecting Stress Distribution in the Root Canal. *Journal of Endodontics,* 29**,** 523-528.

LILLEY, J. D. 1976. Endodontic instrumentation before 1800. *Journal of the British Endodontic Society,* 9**,** 67-70.

LIM, K. & WEBBER, J. 1985a. The validity of simulated root canals for the investigation of the prepared root canal shape. *International endodontic journal,* 18**,** 240-246.

LIM, K. C. & WEBBER, J. 1985b. The validity of simulated root canals for the investigation of the prepared root canal shape. *Int Endod J,* 18.

LIN, L. M., ROSENBERG, P. A. & LIN, J. 2005. Do procedural errors cause endodontic treatment failure? *The Journal of the American Dental Association,* 136**,** 187-193.

MANDEL, E., ADIB-YAZDI, M., BENHAMOU, L. M., LACHKAR, T., MESGOUEZ, C. & SOBEL, M. 1999. Rotary Ni-Ti profile systems for preparing curved canals in resin blocks: influence of operator on instrument breakage. *International Endodontic Journal,* 32**,** 436-443.

MARQUIS, V. L., DAO, T., FARZANEH, M., ABITBOL, S. & FRIEDMAN, S. 2006. Treatment Outcome in Endodontics: The Toronto Study. Phase III: Initial Treatment. *Journal of Endodontics,* 32**,** 299-306.

MCGUIGAN, M. B., LOUCA, C. & DUNCAN, H. F. 2013. Endodontic instrument fracture: causes and prevention. *Br Dent J,* 214**,** 341-348.

MESGOUEZ, C., RILLIARD, F., MATOSSIAN, L., NASSIRI, K. & MANDEL, E. 2003. Influence of operator experience on canal preparation time when using the rotary Ni-Ti ProFile system in simulated curved canals. *International Endodontic Journal,* 36**,** 161-165.

METZGER, Z., TEPEROVICH, E., ZARY, R., COHEN, R. & HOF, R. 2010. The Self-adjusting File (SAF). Part 1: Respecting the Root Canal Anatomy—A New Concept of Endodontic Files and Its Implementation. *Journal of Endodontics,* 36**,** 679-690.

MICKEL, A. K., CHOGLE, S., LIDDLE, J., HUFFAKER, K. & JONES, J. J. 2007. The Role of Apical Size Determination and Enlargement in the Reduction of Intracanal Bacteria. *Journal of Endodontics,* 33**,** 21-23.

MIKROGEORGIS, G., MOLYVDAS, I., LYROUDIA, K., NIKOLAIDIS, N. & PITAS, I. 2006. A new methodology for the comparative study of the root canal instrumentation techniques based on digital radiographic image processing and analysis. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology, and Endodontology,* 101**,** e125-e131.

MOERENHOUT, B. A. M. M. L., GELAUDE, F., SWENNEN, G. R. J., CASSELMAN, J. W., VAN DER SLOTEN, J. & MOMMAERTS, M. Y. 2008. Accuracy and repeatability of cone-beam computed tomography (CBCT) measurements used in the determination of facial indices in the laboratory setup. *Journal of Cranio-Maxillo-Facial Surgery,* 37**,** 18-23.

MORGAN, L. F. & MONTGOMERY, S. 1984. An evaluation of the crown-down pressureless technique. *Journal of Endodontics,* 10**,** 491-498.

MULLANEY, T. P. 1979. Instrumentation of finely curved canals. *Dental Clinics of North America,* 23**,** 575-592.

NAGY, C. D., BARTHA, K., BERNÁTH, M., VERDES, E. & SZABÓ, J. 1997. The effect of root canal morphology on canal shape following instrumentation using different techniques. *International Endodontic Journal,* 30**,** 133-140.

NEVARES, G., XAVIER, F., GOMINHO, L., CAVALCANTI, F., #XE1, VIA, CASSIMIRO, M., ROMEIRO, K., ALVARES, P., QUEIROZ, G., SOBRAL, A. P., GERBI, M., SILVEIRA, M. & ALBUQUERQUE, D. 2015. Apical Extrusion of Debris Produced during Continuous Rotating and Reciprocating Motion. *The Scientific World Journal,* 2015**,** 5.

NG, Y. L., MANN, V., RAHBARAN, S., LEWSEY, J. & GULABIVALA, K. 2007. Outcome of primary root canal treatment: systematic review of the literature – Part 1. Effects of study characteristics on probability of success. *International Endodontic Journal,* 40**,** 921-939.

NIELSEN, R. B., ALYASSIN, A. M., PETERS, D. D., CARNES, D. L. & LANCASTER, J. 1995. Microcomputed tomography: An advanced system for detailed endodontic research. *Journal of Endodontics,* 21**,** 561-568.

OKANO, T., HARATA, Y., SUGIHARA, Y., SAKAINO, R., TSUCHIDA, R., IWAI, K., SEKI, K. & ARAKI, K. 2009. Absorbed and effective doses from cone beam volumetric imaging for implant planning. *Dentomaxillofacial Radiology,* 38**,** 79-85.

ORDINOLA-ZAPATA, R., BRAMANTE, C. M., VERSIANI, M. A., MOLDAUER, B. I., TOPHAM, G., GUTMANN, J. L., NUÑEZ, A., DUARTE, M. A. H. & ABELLA, F. 2016. Comparative accuracy of the Clearing Technique, CBCT and Micro-CT methods in studying the mesial root canal configuration of mandibular first molars. *International Endodontic Journal***,** n/a-n/a.

PAQUÉ, F., BALMER, M., ATTIN, T. & PETERS, O. A. 2009. Preparation of Oval-shaped Root Canals in Mandibular Molars Using Nickel-Titanium Rotary Instruments: A Micro-computed Tomography Study. *Journal of Endodontics,* 36**,** 703-707.

PAQUÉ, F. & PETERS, O. A. 2011. Micro–computed Tomography Evaluation of the Preparation of Long Oval Root Canals in Mandibular Molars with the Self-adjusting File. *Journal of Endodontics,* 37**,** 517-521.

PATEL, S. 2013. Chapter 5,The Principles of Endodontics. Second Edition.

PATEL, S. & RHODES, J. 2007. A practical guide to endodontic access cavity preparation in molar teeth. *Br Dent J,* 203**,** 133-140.

PÉREZ-HIGUERAS, J. J., ARIAS, A., DE LA MACORRA, J. C. & PETERS, O. A. 2014. Differences in Cyclic Fatigue Resistance between ProTaper Next and ProTaper Universal Instruments at Different Levels. *Journal of Endodontics,* 40**,** 1477-1481.

PETERS, O. A. 2004. Current Challenges and Concepts in the Preparation of Root Canal Systems: A Review. *Journal of Endodontics,* 30**,** 559-567.

PETERS, O. A., LAIB, A., GÖHRING, T. N. & BARBAKOW, F. 2001a. Changes in Root Canal Geometry after Preparation Assessed by High-Resolution Computed Tomography. *Journal of Endodontics,* 27**,** 1-6.

PETERS, O. A. & PAQUE, F. 2010. Current developments in rotary root canal instrument technology and clinical use: a review. *Quintessence international (Berlin, Germany: 1985),* 41**,** 479-488.

PETERS, O. A. & PAQUÉ, F. 2011. Root Canal Preparation of Maxillary Molars With the Self-adjusting File: A Micro-computed Tomography Study. *Journal of Endodontics,* 37**,** 53-57.

PETERS, O. A., SCHÖNENBERGER, K. & LAIB, A. 2001b. Effects of four Ni–Ti preparation techniques on root canal geometry assessed by micro computed tomography. *International Endodontic Journal,* 34**,** 221-230.

PLOTINO, G., GRANDE, N. M., MERCADÉ BELLIDO, M., TESTARELLI, L. & GAMBARINI, G. 2017. Influence of Temperature on Cyclic Fatigue Resistance of ProTaper Gold and ProTaper Universal Rotary Files. *Journal of Endodontics,* 43**,** 200-202.

PLOTINO, G., GRANDE, N. M., PECCI, R., BEDINI, R., PAMEIJER, C. H. & SOMMA, F. 2006. Three-dimensional imaging using microcomputed tomography for studying tooth macromorphology. *The Journal of the American Dental Association,* 137**,** 1555-1561.

PRATI, C., FOSCHI, F., NUCCI, C., MONTEBUGNOLI, L. & MARCHIONNI, S. 2004. Appearance of the root canal walls after preparation with NiTi rotary instruments: a comparative SEM investigation. *Clinical Oral Investigations,* 8**,** 102-110.

PRICHARD, J. 2012. Rotation or reciprocation: a contemporary look at NiTi instruments? *Br Dent J,* 212**,** 345-346.

QUALTROUGH, A. J. E. & DUMMER, P. M. H. 1997. Undergraduate endodontic teaching in the United Kingdom: an update. *International Endodontic Journal,* 30**,** 234-239.

QUALTROUGH, A. J. E., WHITWORTH, J. M. & DUMMER, P. M. H. 1999. Preclinical endodontology: an international comparison. *International Endodontic Journal,* 32**,** 406-414.

RAPISARDA, E., BONACCORSO, A., TRIPI, T. R., FRAGALK, I. & CONDORELLI, G. G. 2000. The effect of surface treatments of nickel-titanium files on wear and cutting efficiency. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology, and Endodontology,* 89**,** 363-368.

REE, M. H., TIMMERMAN, M. F. & WESSELINK, P. R. 2003. An evaluation of the usefulness of two endodontic case assessment forms by general dentists. *International Endodontic Journal,* 36**,** 545-555.

ROANE, J. B., SABALA, C. L. & DUNCANSON JR, M. G. 1985. The "balanced force" concept for instrumentation of curved canals. *Journal of Endodontics,* 11**,** 203-211.

ROBERTSON, D. C. & LEEB, J. 1982. The evaluation of a transparent tooth model system for the evaluation of endodontically filled teeth. *Journal of Endodontics,* 8**,** 317-321.

RUDDLE, C. J., MACHTOU, P. & WEST, J. D. 2013. The shaping movement 5th generation technology. *Dentistry today*.

SCHÄFER, E. 1997. Root canal instruments for manual use: a review. *Dental Traumatology,* 13**,** 51-64.

SCHILDER, H. 1974. Cleaning and shaping the root canal. *Dental Clinics of North America,* 18**,** 269-296.

SCHNEIDER, S. W. 1971. A comparison of canal preparations in straight and curved root canals. *Oral Surg Oral Med Oral Pathol,* 32.

SHAPIRO, L. G. & STOCKMAN, G. C. 2001. *Computer vision,* Upper Saddle River, NJ : Prentice Hall, 2001.

SIQUEIRA, J. F. 2001. Aetiology of root canal treatment failure: why well-treated teeth can fail. *International Endodontic Journal,* 34**,** 1-10.

SIQUEIRA, J. F., ARAÚJO, M. C., GARCIA, P. F., FRAGA, R. C. & DANTAS, C. J. S. 1997. Histological evaluation of the effectiveness of five instrumentation techniques for cleaning the apical third of root canals. *Journal of Endodontics,* 23**,** 499-502.

SJÖGREN, U., HÄGGLUND, B., SUNDQVIST, G. & WING, K. 1990. Factors affecting the long-term results of endodontic treatment. *Journal of Endodontics,* 16**,** 498-504.

STOCK, S. R. 2008. *MicroComputed Tomography: Methodology and Applications,* CRC Press.

SWAIN, M. V. & XUE, J. 2009. State of the Art of Micro-CT Applications in Dental Research. *International Journal of Oral Science,* 1**,** 177-188.

TCHORZ, J. P., BRANDL, M., GANTER, P. A., KARYGIANNI, L., POLYDOROU, O., VACH, K., HELLWIG, E. & ALTENBURGER, M. J. 2014. Pre-clinical endodontic training with artificial instead of extracted human teeth: does the type of exercise have an influence on clinical endodontic outcomes? *Int Endod J*.

THOMPSON, S. A. 2000. An overview of nickel–titanium alloys used in dentistry. *International Endodontic Journal,* 33**,** 297-310.

URANGA, A., BLUM, J.-Y., ESBER, S., PARAHY, E. & PRADO, C. 1999. A comparative study of four coronal obturation materials in endodontic treatment. *Journal of Endodontics,* 25**,** 178-180.

VERSIANI, M. A., PÉCORA, J. D. & SOUSA-NETO, M. D. 2011. The anatomy of two-rooted mandibular canines determined using micro-computed tomography. *International Endodontic Journal,* 44**,** 682-687.

VERTUCCI, F. J. 2005. Root canal morphology and its relationship to endodontic procedures. *Endodontic Topics,* 10**,** 3-29.

WALTON, R. E. 1976. Histologic evaluation of different methods of enlarging the pulp canal space. *Journal of Endodontics,* 2**,** 304-311.

WANG, N., KNIGHT, K., DAO, T. & FRIEDMAN, S. 2004. Treatment Outcome in Endodontics—The Toronto Study. Phases I and II: Apical Surgery. *Journal of Endodontics,* 30**,** 751-761.

WAPLINGTON, M. & MCROBERT, A. 2014. Shaping the root canal system. *British dental journal,* 216**,** 293-297.

WEINE, F. S., KELLY, R. F. & LIO, P. J. 1975. The effect of preparation procedures on original canal shape and on apical foramen shape. *Journal of Endodontics,* 1**,** 255-262.

WIGLER, R., DVIR, R., WEISMAN, A., MATALON, S. & KFIR, A. 2017. Efficacy of XP-endo finisher files in the removal of calcium hydroxide paste from artificial standardized grooves in the apical third of oval root canals. *International Endodontic Journal,* 50**,** 700-705.

WU, H., PENG, C., BAI, Y., HU, X., WANG, L. & LI, C. 2015. Shaping ability of ProTaper Universal, WaveOne and ProTaper Next in simulated L-shaped and S-shaped root canals. *BMC Oral Health,* 15**,** 1-7.

WU, M. K. & WESSELINK, P. R. 1993. Endodontic leakage studies reconsidered. Part I. Methodology, application and relevance. *International Endodontic Journal,* 26**,** 37-43.

XI, T., SCHREURS, R., HEERINK, W. J., BERGÉ, S. J. & MAAL, T. J. J. 2014. A Novel Region-Growing Based Semi-Automatic Segmentation Protocol for Three-Dimensional Condylar Reconstruction Using Cone Beam Computed Tomography (CBCT). *PLoS ONE,* 9**,** e111126.

YARED, G. 2008. Canal preparation using only one Ni-Ti rotary instrument: preliminary observations. *International Endodontic Journal,* 41**,** 339-344.

ZHOU, H., PENG, B. & ZHENG, Y.-F. 2013. An overview of the mechanical properties of nickel–titanium endodontic instruments. *Endodontic Topics,* 29**,** 42-54.

Appendices

8.1 Appendix 1: Publication of the 1st study in ENDO endodontic practice today

Emad Moawad, Katherine Blundell, Antony Preston, Fadi Jarad

An investigation of technical outcome and procedural errors produced by novice operators with ProTaper Universal and ProTaper Next nickel titanium instruments in simulated root canals

Key words *procedural errors, ProTaper Universal, ProTaper Next, rotary*

Objective: To investigate technical outcome and time efficiency, using ProTaper Universal (PTU) or ProTaper Next (PTN) rotary nickel titanium (NiTi) files, to prepare simulated canals, by undergraduate dental students.
Methods: Sixty-six students were randomly assigned to two groups. Both groups prepared two endodontic blocks (n = 66) using PTU and PTN in crossover design. Preparation time was also recorded. The blocks were photographed under magnification and were assessed for procedural errors by two different observers. Data were recorded and analysed by descriptive statistics, generalised mixed model and analysis of variance (ANOVA) using SPSS.
Results: The different file systems had a significant effect on the presence or absence of procedural errors, with a significance value of $P < 0.001$. More successful preparation was achieved with PTN (89%) than PTU (37.5%). There were a total number of procedural errors of n = 58.The highest incidence of procedural errors by different file systems was transportation. The PTU showed 24 transportation errors out of a total of 51 errors and the PTN showed five transportation errors out of a total of seven. PTN demonstrated the quickest mean time of preparation with a P value of $P < 0.001$.
Conclusion: In the hands of novice operators, PTN showed a lower incidence of procedural errors and better time efficacy during instrumentation of simulated canals, compared with PTU.

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■ Introduction

The shaping of a root canal system can be highly challenging, due to the complexity and variation of root canal anatomy[1]. The outcome of root canal treatment has been directly linked to the quality of mechanical and chemical debridement of the root canal system; iatrogenic alterations to the original canal shape will affect the debridement process and the treatment outcome, especially in infected root canals[2]. In a non-infected canal, the presence of a procedural error would still affect the debridement process, however it does not have as much impact on the treatment outcome due to the absence of pathogens[2]. Historically, mechanical preparation of root canals was undertaken using stainless steel hand files, but now hand and motor-driven NiTi files are more common. Although the operator needs a reasonable amount of experience[3,4], these files can decrease the incidence of procedural errors during root canal shaping. Inexperienced operators may still produce procedural errors when using NiTi files; this could reduce their confidence and discourage some from performing endodontics[5,6].

Although there is no standardised protocol for pre-clinical teaching it is common practice to use a combination of root canal models, whether they are simulated teeth or resin blocks with simulated

ENDO (Lond Engl) 2017;11(1):23–29

8.2 Appendix 2: Abstract accepted for publication in international endodontic journal

Preparation: Shaping ability

An investigation of the efficacy of instrumentation in mandibular molars using the XP-endo Shaper NiTi rotary file: a micro CT analysis.

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Aim To investigate the percentage of root canal surface instrumentation achieved by XP-endo Shaper rotary NiTi file (FKG Dentaire SA, Switzerland) in mandibular molars, using micro computed tomography (µCT) imaging and three dimensional analysis

Methodology Thirty-seven mandibular molars were scanned and reconstructed using µCT scannner at a high resolution. Twelve molars were selected from the prepreparation scans, taking into account the canal space volume, canal anatomy, degree of curvature and canal dimensions. The molars were scanned with µCT at 20 µm resolution pre-preparation and post preparation with the XP-endo Shaper (XPS). A single operator undertook all the preparation. Images were manipulated and reconstructed in three dimensions, to allow superimposition and analysis using image analysis software (Materialise mimic package, Leuven Belgium). Data were recorded and analysed in SPSS 24 software using Univariate analysis and descriptive statistics.

Results The difference in mean of canal space volume between pre and post preparation images is= 414989.17 μm^3, SD = 518793.9 (95 % C.I =195921.72-634056.6). The mean percentage of root canal instrumentation was 62.61%, SD = 15.97, 95 % C I =55.46 –68.95. The difference in root canal space volume was mainly affected by the pre operative volume of the canal ($P< 0.001$). All other variables did not show any significant effect. No file fracture or procedural errors were detected with the XPS.

Conclusions Within the limitations of the study, the XP-endo Shaper demonstrated a high percentage of root canal surface instrumentation. The percentage of surface instrumentation is comparable and was shown to exceed that stated previously in the literature. The efficacy of the XPS was affected in some canals by the pre-preparation canal volume..

8.3 Appendix 3: Poster presented in the biennial congress of the European society of endodontics, Brussels September 2017

An investigation of the efficacy of instrumentation in mandibular molars using XP-endo Shaper Ni Ti rotary file : a micro CT analysis.

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Department of Restorative Dentistry, School of Dentistry, University of Liverpool, Liverpool, United Kingdom

Introduction

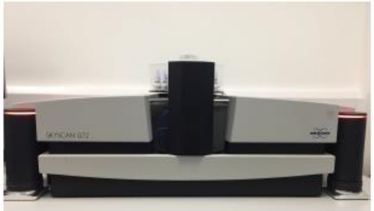
- The root canal system is highly complex; canal shape can vary from tooth to tooth and even between roots of the same tooth.
- Different studies, such as dye and micro CT studies discovered this complexity.
- This explains the difficulty in accessing or fully reaching of some areas inside the root canal system. In the face of such complexity, standard NiTi files are not always ideal for root canal instrumentation.
- Several studies involving micro CT technologies have shown that, on the whole, when standard NiTi files are used to prepare the root canal, only 40-70 percent of canal walls are actually instrumented.
- The recently introduced instruments are XP-endo shapers (XPS) and XP-endo finishers (XPF) (FKG Dentaire SA).
- The manufacturer claims that XPS allow better mechanical preparation and better instrumentation efficacy of the canal walls in areas previously impossible to instrument. The efficacy can go up to three times more than the conventional instruments.

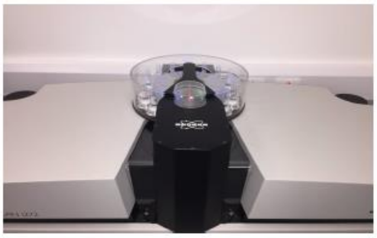
Aim

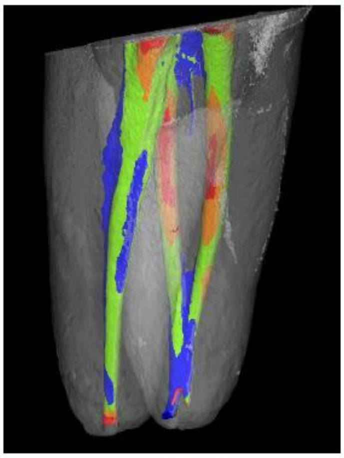
- To investigate the percentage of root canal surface instrumentation achieved by XP-endo Shaper rotary NiTi file (FKG Dentaire SA, Switzerland) in mandibular molars, using micro computed tomography (µCT) imaging and three dimensional analysis

Methodology

- Thirty-seven mandibular molars were scanned and reconstructed using µCT scanner at a high resolution.
- Twelve molars were selected from the pre-preparation scans, taking into account the canal space volume, canal anatomy, degree of curvature and canal dimensions.
- The molars were scanned with µCT at 20 µm resolution pre-preparation and post preparation with the XP-endo Shaper (XPS).
- A single operator undertook all the preparation.
- Images were manipulated and reconstructed in three dimensions, to allow superimposition and analysis using image analysis software (Materialise mimic package, Leuven, Belgium).
- Data were recorded and analysed in SPSS 24 software using Univariate analysis and descriptive statistics.

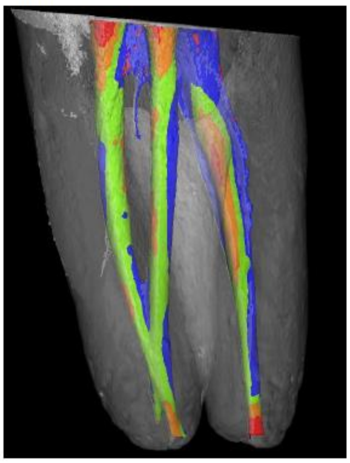






Results

- The difference in the mean canal space volume between pre and post preparation images is 414989.17 µm³, SD = 518793.9 (95 % C.I =195921.72-634056.6).
- The mean percentage of root canal instrumentation was 62.61%, SD = 15.97, 95 % C I =55.46 –68.95.
- The difference in root canal space volume was mainly affected by the pre operative volume of the canal ($P < 0.001$).
- No file fracture or procedural errors were detected with the XPS.



Conclusion

- Within the limitations of the study, the XP-endo Shaper demonstrated a high percentage of root canal surface instrumentation.
- The percentage of surface instrumentation is comparable and was shown to exceed that stated previously in the literature.
- The efficacy of the XPS was affected in some canals by the pre-preparation canal volume.

Bibliography

- Plotino G, Grande NM, Pecci R, Bedini R, Pameijer CH, Somma F. Three-dimensional imaging using microcomputed tomography for studying tooth macromorphology. The Journal of the American Dental Association. 2006;137(11):1555-61.
- Swain MV, Xue J. State of the Art of Micro-CT Applications in Dental Research. International Journal of Oral Science. 2009;1(4):177-88.
- Peters OA, Schönenberger K, Laib A. Effects of four Ni–Ti preparation techniques on root canal geometry assessed by micro computed tomography. International endodontic journal. 2001;34(3):221-30.

Acknowledgements

- The authors deny any conflict of interest related to this study.
- The authors thank **FKG Dentaire SA** and **Schottlander UK** for providing the instruments used in the study.

8.4 Appendix 4: Ethical approval application

UNIVERSITY OF LIVERPOOL

COMMITTEE ON RESEARCH ETHICS

APPLICATION FOR APPROVAL OF A PROJECT INVOLVING HUMAN PARTICIPANTS, HUMAN DATA, OR HUMAN MATERIAL

NOTES

1) This application form is to be used by researchers seeking research ethics approval from the University, as per the University's Policy on Research Ethics involving Human Participation. If an application qualifies for expedited review (Section C) it may be reviewed at Level 2, by your School or Institute's research ethics process.

2) Applications to the University Research Ethics Committees must normally include an **application form, participant information sheet and consent form** (all templates available online), along with any other relevant information, and should be submitted by email to the relevant contact listed at http://www.liv.ac.uk/researchethics/apply,for,research,ethics/.

3) Applications from Student investigators: the Committee will require proof that your Supervisor has approved the application to be submitted. Please attach this to your email. Your supervisor must be copied in on all correspondence relating to your application.

4) This form must be completed by following the guidance notes, accessible at www.liv.ac.uk/researchethics. Please complete every section, using N/A if appropriate. Incomplete forms will be returned to the applicant.

5) For studies involving overseas sites, please ensure you have researched any local approvals that might be required. Wherever possible this should include local research ethics approval. In the absence of a research ethics approval body, other relevant local approvals should be obtained, e.g. authorisation from a site, letter from a local organisation or group etc.

6) This form does not constitute insurance approval which must be sought separately. Please contact the **University's Insurance and Risk Manager** if your project involves overseas sites, vulnerable groups or is a clinical trial.

7) Staff investigators: You are encouraged to discuss your proposal with your Head of Department prior to submitting for research ethics approval.

RESEARCH MUST NOT BEGIN UNTIL ETHICAL APPROVAL HAS BEEN OBTAINED

FAILURE TO SEEK RESEARCH ETHICS APPROVAL IS TAKEN EXTREMELY SERIOUSLY BY THE INSTITUTION.

BEFORE COMPLETING YOUR APPLICATION PLEASE CONFIRM WHAT APPROVAL YOU ARE SEEKING (please check with “x”)**:**

a) Expedited review of an individual research project ......X......

b) Full committee review of an individual research project ....

c) Committee review generic* approval ....

*to cover a cohort of projects using similar methodologies and in line with Policy on Generic Approvals which can be found at www.liv.ac.uk/researchethics . Boundaries of the research must be defined clearly. Approval may be granted for up to 3 years and will be subject to annual review.

Declaration of the:

Principal Investigator ____X____ **OR** **Supervisor and Student Investigator** __________
(please check with a "x")

- The information in this form is accurate to the best of my knowledge and belief, and I take full responsibility for it.
- I have read and understand the University's Policy on Research Ethics
- I undertake to abide by the ethical principles underlying the Declaration of Helsinki and the University's good practice guidelines on the proper conduct of research, together with the codes of practice laid down by any relevant professional or learned society.
- If the research is approved, I undertake to adhere to the study plan, the terms of the full application of which the REC has given a favourable opinion, and any conditions set out by the REC in giving its favourable opinion.
- I undertake to seek an ethical opinion from the REC before implementing substantial amendments to the study plan or to the terms of the full application of which the REC has given a favourable opinion.
- I understand that I am responsible for monitoring the research at all times.
- If there are any serious adverse events, I understand that I am responsible for immediately stopping the research and alerting the Research Ethics Committee within 24 hours of the occurrence, via ethics@liv.ac.uk.
- I am aware of my responsibility to be up to date and comply with the requirements of the law and relevant guidelines relating to security and confidentiality of personal data.
- I understand that research records/data may be subject to inspection for audit purposes if required in future.
- I understand that personal data about me as a researcher in this application will be held by the University and that this will be managed according to the principles established in the Data Protection Act.
- I understand that the information contained in this application, any supporting documentation and all correspondence with the Research Ethics Committee relating to the application, will be subject to the provisions of the Freedom of Information Acts. The information may be disclosed in response to requests made under the Acts except where statutory exemptions apply.
- I understand that all conditions apply to any co-applicants and researchers involved in the study, and that it is my responsibility to ensure that they abide by them.
- **For Supervisors**: I understand my responsibilities as supervisor, and will ensure, to the best of my abilities, that the student investigator abides by the University's Policy on Research Ethics at all times.
- **For the Student Investigator**: I understand my responsibilities to work within a set of safety, ethical and other guidelines as agreed in advance with my supervisor and understand that I must comply with the University's regulations and any other applicable code of ethics at all times.

Signature of Principal Investigator **or** **Supervisor:**
Date: (dd/mm/yyyy)
Print Name:

Signature of Student Investigator:

Emad Moawad

Date: 08/10/2015
Print Name: Emad Moawad

SECTION A - IDENTIFYING INFORMATION

A1) **Title of the research** *(PLEASE INCLUDE A SHORT LAY TITLE IN BRACKETS).*

Shaping and cleaning in endodontics

A2) **PRINCIPAL INVESTIGATOR**

Title:	Dr	**Staff number:**	
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A3) **Student Investigator(s)**

Title and Name	**Post / Current programme (if student investigator)**	**Department/ School/Institution if not UoL**	**Phone**	**Email**
Dr Fadi Jarad	SCL at the Dental School. DDSC. Program director	Restorative Dentistry, Dental School		fjarad@liverpool.ac.uk
Miss Kate Blundell	Clinical Teacher	Restorative Dentistry, Dental School		K.E.Blundell@liverpool.ac.uk
Mr Emad Moawad	PG student at DDSc. In endodontics program	Restorative Dentistry, Dental School		emoawad@liverpool.ac.uk

SECTION B - PROJECT DETAILS

B1) **Proposed study dates and duration** (RESEARCH **MUST NOT BEGIN** UNTIL ETHICAL APPROVAL HAS BEEN OBTAINED)

Please complete as appropriate:

EITHER

a) **Starting as soon as ethical approval has been obtained**

YES

Approximate end date:	September 2017

B2) **Give a FULL LAY SUMMARY of the purpose, design and methodology of the planned research.** *N.B. Please use as little jargon or technical language as possible. Where jargon / technical language is unavoidable, please ensure you provide a lay explanation. Please define any acronyms. The summary must be understood by persons outside of the subject area including members of the general public*

Aim:

The aim of the study is to compare the effect of a new nickel-titanium file root canal preparation technique against the conventional preparation technique (control group), in terms of shaping efficiency, achieving 3D shaping and the amount of dentine removed inside the canal, using micro CT analysis.

Methodology:

The sample size will be approximately 20 molars (60 root canals). They will be provided by the Dental School, after the University Ethical Approval is granted. The teeth will be split into two groups of 10 molars each. The teeth will be scanned with micro CT before undergoing preparation. Half of teeth will be prepared with the conventional technique (pro-taper Next X1 size 17mm tip,0.4 % taper- X2 size 25mm tip, 0.6 % taper) control group; the other group teeth will be prepared by a new NiTi files technique (Pro-taper Next X1, X2 + XP-endo Finisher size 25mm tip with 0.0 % taper) The teeth will then be scanned again with Micro CT, after three dimensional images will be reconstructed by specific software and then the images will be analysed and compared for changes in root canal volume, amount of dentine removed and the amount of canal surface area instrumented by the files.

Implications:

- The study will examine a new preparation technique with a new finisher file (XP Endo Finisher) added to the sequence which will try to achieve 3D shaping and instrument all root canal's surface area. The literature states that about 35%-60% of the canals' surface area is un-instrumented by rotary Nickel-Titanium files. Also I will be looking for more dentine preservation which is the modern request in dental treatment to be more conservative and preserve more tooth structure to have better strength and physical properties.

Ethical concerns regarding the teeth:

- The teeth at the Dental School were collected for teaching purposes and consents were taken verbally and recorded in case notes and teeth were anonymized.

- Based on the HTA codes of practice for consents and research, as long teeth are anonymised there is no need for a specific consent.
  Codes 36,61,64, 127

36. To ensure that the removal, storage or use of any tissue is lawful, it is important to establish clearly that consent has been given. Consent may be expressed in various ways, and does not necessarily need to be in writing, unless the HT Act requires it to be (see section on format of consent, paragraphs 61-65). Obtaining valid consent presupposes that there is a process in which individuals, including their families where appropriate, may discuss the issue fully, ask questions and make an informed choice.

61. The HT Act does not specify the format in which consent should be given or recorded, except for anatomical examination or public display which must be in writing (see section on written consent, paragraphs 110-113). The information required and the manner in which consent is obtained and recorded may vary depending on the particular circumstances.

64. When consent is obtained but it is not in writing, for example for future storage or use of samples, this should be clearly documented in the patient's records, the laboratory records or both. The record should detail when consent was obtained and the purposes for which the consent was given

127.Tissue from the living may be stored or used without consent, provided that:

1. The researcher is not in possession, and not likely to come into possession of information that identifies the person from whom it has come; and the material is used for a specific research project with ethical approval.

- Concerning the registration with the University designated human tissue individual, I have already discussed the project with Dr. Janet Risk and she will send me a simple form to fill after getting the ethical approval.

.

B3) **List any research assistants, sub-contractors or other staff not named above who will be involved in the research and detail their involvement.**

B4) **List below all research sites, and their Lead Investigators, to be included in this study.**

Research Site	Individual Responsible	Position and contact details
Dental school, University of Liverpool	Dr Antony Preston	Senior Clinical Lecturer at the Dental School.

B5) **Are the results of the study to be disseminated in the public domain?**

YES

B6) **Give details of the funding of the research, including funding organisation(s), amount applied for or secured, duration, and University of Liverpool reference**

Funding Body	Amount	Duration	UoL Reference

B7) **Give details of any interests, commercial or otherwise, you or your co-applicants have in the funding body.**

N/A

SECTION C - EXPEDITED REVIEW

C1)

a) Will the study involve recruitment of participants outside the UK? *For studies involving overseas sites, please ensure you have researched any local approvals that might be required. Wherever possible this should include local research ethics approval. In the absence of a research ethics approval body, other relevant local approvals should be obtained, e.g. authorisation from a site, letter from a local organisation or group etc.*	No
b) Does the study involve participants who are particularly vulnerable or unable to give informed consent? *(e.g. children, people with learning or communication disabilities, people in custody, people engaged in illegal activities such as drug-taking, your own students in an educational capacity) (Note: this does not include secondary data authorised for release by the data collector for research purposes.)*	No
c) Will the study require obtaining consent from a "research participant advocate" (for definition see guidance notes) in lieu of participants who are unable to give informed consent? *(e.g. for research involving children or, people with learning or communication disabilities)*	No
d) Will it be necessary for participants, whose consent to participate in the study will be required, to take part without their knowledge at the time? *(e.g. covert observation using photography or video recording)*	No
e) Does the study involve deliberately misleading the participants?	No
f) Will the study require discussion of sensitive topics that may cause distress or embarrassment to the participant or potential risk of disclosure to the researcher of criminal activity or child protection issues? *(e.g. sexual activity, criminal activity)*	No
g) Are drugs, placebos or other substances (e.g. food substances, vitamins) to be administered to the study participants or will the study involve invasive, intrusive or potentially harmful procedures of any kind?	No
h) Will samples (e.g. blood, DNA, tissue) be obtained from participants?	No
i) Is pain or more than mild discomfort likely to result from the study?	No
j) Could the study induce psychological stress or anxiety or cause harm or negative consequences beyond the risks encountered in normal life?	No
k) Will the study involve prolonged or repetitive testing?	No
l) Will financial inducements (other than reasonable expenses and compensation for time) be offered to participants?	No

C2)

a) Will the study seek written, informed consent?	No
b) Will participants be informed that their participation is voluntary?	No
c) Will participants be informed that they are free to withdraw at any time?	No
d) Will participants be informed of aspects relevant to their continued participation in the study?	No
e) Will participants' data remain confidential?	No
f) Will participants be debriefed?	No

If you have answered 'no' to all items in SECTION C1 and 'yes' to all questions in SECTION C2 the application will be processed through expedited review.

If you have answered "Yes" to one or more questions in Section C1, or "No" to one or more questions in Section C2, but wish to apply for expedited review, please make the case below.

C3) **Case for Expedited Review –** *To be used if asking for expedited review despite answering YES to questions in C1 or NO to answers in C2.*

SECTION D - PARTICIPANT DETAILS

D1) **How many participants will be recruited?**

No participants to be recruited , I am just using anonymised extracted teeth

D2) **How was the number of participants decided upon?**

No participants

D3)

a) **Describe how potential participants in the study will be identified, approached and recruited.**

No participants in the study

b) **Inclusion criteria:**

No inclusion criteria

c) **Exclusion criteria:**

No exclusion criteria

d) **Are any specific groups to be excluded from this study? If so please list them and explain why:**

No specific groups

e) **Give details for cases and controls separately if appropriate:**

Not applicable

f) **Give details of any advertisements:**

Not applicable

D4)

a) **State the numbers of participants from any of the following vulnerable groups and justify their inclusion**

Children under 16 years of age:	
Adults with learning disabilities:	
Adults with dementia:	
Prisoners:	
Young Offenders:	
Adults who are unable to consent for themselves:	
Those who could be considered to have a particularly dependent relationship with the investigator, e.g. those in care homes, students of the PI or Co-applicants:	
Other vulnerable groups (please list):	

b) **State the numbers of healthy volunteer participants:**

Healthy Volunteers	

D5)

a) **Describe the arrangements for gaining informed consent from the research participants.**

No participants to be recruited

b) **If participants are to be recruited from any of the potentially vulnerable groups listed above, give details of extra steps taken to assure their protection, including arrangements to obtain consent from a legal, political or other appropriate representative in addition to the consent of the participant** *(e.g. HM Prison Service for research with young offenders, Head Teachers for research with children etc.).*

No participants to be recruited

c) **If participants might not adequately understand verbal explanations or written information given in English, describe the arrangements for those participants** *(e.g. translation, use of interpreters etc.)*

No participants to be recruited

d) **Where informed consent is not to be obtained (including the deception of participants) please explain why.**

No participants

D6) **What is the potential for benefit to research participants, if any?**

No participants to be recruited

D7) **State any fees, reimbursements for time and inconvenience, or other forms of compensation that individual research participants may receive. Include direct payments, reimbursement of expenses or any other benefits of taking part in the research?**

No fees or any forms of compensation - no participants

SECTION E - RISKS AND THEIR MANAGEMENT

***NOTE**: Completing section E fulfils the requirement for risk assessment, provided that this section is reviewed if circumstances change, or new information makes it necessary.*

A copy of this form should be given to your departmental safety coordinator to enable monitoring of risk assessments. The findings of the risk assessment, especially the precautions required, must be communicated in a user-friendly way to all those doing this work.

E1) **Describe in detail the potential physical or psychological adverse effects, risks or hazards (minimal, moderate, high or severe) of involvement in the research for research participants.**

No participants involved in the study

E2) **Explain how the potential benefits of the research outweigh any risks to the participants.**

No participants involved in the study

E3) **Describe in detail the potential adverse effects, risks or hazards (minimal, moderate, high or severe) arising from this research to the researchers or anyone else.**

No participants involved in the study

E4) **What precautions will be in place to minimise the risks identified in E1 and E3?**

No participants involved in the study

E5) **Will individual or group interviews/questionnaires discuss any topics or issues that might be sensitive, embarrassing or upsetting, or is it possible that criminal or other disclosures requiring action could take place during the study** (e.g. during interviews/group discussions, or use of screening tests for drugs)**?**
NO

E6) **Describe the measures in place in the event of any unexpected outcomes or adverse events to participants arising from their involvement in the project**

No participants involved in the study

E7) **Explain how the conduct of the project will be monitored to ensure that it conforms with the study plan and relevant University policies and guidance.**

The study will be conducted under the supervision of the PI following the guidelines of the

SECTION F - DATA ACCESS AND STORAGE

F1) **Where the research involves any of the following activities at any stage (including identification of potential research participants), state what measures have been put in place to ensure confidentiality of personal data** *(e.g. encryption or other anonymisation procedures will be used).*

**PLEASE NOTE THAT UNLESS THERE ARE EXCEPTIONAL CIRCUMSTANCES, ALL DATA MUST BE HELD SECURELY ON THE "M" DRIVE AND IN LINE WITH UNIVERSITY POLICY. VISIT THE CSD WEBPAGES FOR FURTHER INFORMATION*

Electronic transfer of data by magnetic or optical media, e-mail or computer networks	Might be possible and will happen either through the University drive or a password-protected memory stick
Sharing of data with other organisations	Not applicable
Exporting data outside the European Union	Not exporting data anywhere
Use of personal addresses, postcodes, faxes, e-mails or telephone numbers	All the data will not involve human data and the teeth I am using are anonymised
Publication of direct quotations from respondents	Not applicable
Publication of data that might allow identification of individuals	All the extracted teeth I am using are anonymised and will not allow identification of any individuals
Use of audio/visual recording devices	Not applicable
Storage of personal data on any of the following:	
Manual files	
Home or other personal computers	*DATA MUST ONLY BE STORED ON THE UNIVERSITY'S SECURE SERVER, YOU CAN GAIN REMOTE ACCESS TO THE SECURE SERVER VIA THE UNIVERSITY'S APPS ANYWHERE APPLICATION.**
University computers	*DATA MUST ONLY BE STORED ON THE UNIVERSITY'S SECURE SERVER, YOU CAN GAIN REMOTE ACCESS TO THE SECURE SERVER VIA THE UNIVERSITY'S APPS ANYWHERE APPLICATION.**
Private company computers	*DATA MUST ONLY BE STORED ON THE UNIVERSITY'S SECURE SERVER, YOU CAN GAIN REMOTE ACCESS TO THE SECURE SERVER VIA THE UNIVERSITY'S APPS ANYWHERE APPLICATION.**
Laptop computers	*DATA MUST ONLY BE STORED ON THE UNIVERSITY'S SECURE SERVER, YOU CAN GAIN REMOTE ACCESS TO THE SECURE SERVER VIA*

	*THE UNIVERSITY'S APPS ANYWHERE APPLICATION.**

F2) Who will have control of and act as the PRIMARY custodian for the data generated by the study?

SUPERVISORS / PRINCIPAL INVESTIGATOR/Myself

F3) who will have access to the data generated by the study?

Supervisors and research Student conducting the study

F4) For how long will data from the study be stored?

5 years

SECTION G – PEER REVIEW AND TRAINING

G1) a) Has the project undergone peer review?

YES

b) If yes, by whom was this carried out? *(please enclose evidence if available)*

Principle investigator

G2) a) What date was your most recent training in research ethics?

Date:	20/11/2014

b) Please provide details of the training provider and course:

Training provider:	NIHR CRN
Course title:	Introduction to Good Clinical Practice (GCP): A practical guide to ethical and scientific quality Standards in clinical research

8.5 Appendix 5: ethical approval letter

UNIVERSITY OF LIVERPOOL

School of Medicine

Faculty of Health and Life Sciences
Cedar House
Ashton Street
Liverpool
L69 3GE

T: 0151 795 4356
F: 0151 794 8763
W: www.liv.ac.uk

9th February 2016

Dear Antony

I am pleased to inform you that the ILT Ethics Review Group (staff) has approved your application for ethical approval. However, the reviewers made the following comments:

"Please pay attention to punctuation and grammar as Ethical Applications are official documents."

Details of the approval can be found below:

Ref:	201610119
PI/Supervisor:	Antony Preston
Title:	Shaping and cleaning in endodontics
First Reviewer:	Helen Orton
Second Reviewer:	Simon Watmough
Date of Approval:	20th January 2016

The application was APPROVED subject to the following conditions:

Conditions

1 All serious adverse events must be reported to the Sub-Committee within 24 hours of their occurrence, via the Research Governance Officer (ethics@liv.ac.uk).

2 This approval applies for the duration of the research. If it is proposed to extend the duration of the study as specified in the application form, IPHS REC should be notified as follows. If it is proposed to make an amendment to the research, you should notify IP IPHS REC by following the Notice of Amendment procedure outlined at http://www.liv.ac.uk/researchethics/amendment%20procedure%209-08.doc

3 If the named PI / Supervisor leaves the employment of the University during the course of this approval, the approval will lapse. Therefore please contact the Institute's Research Ethics Office at iphsrec@liverpool.ac.uk in order to notify them of a change in PI/Supervisor.

Best wishes and good luck with the study.

Ann Furlong

Ann Furlong

ILT Ethics Review Group (Staff) Secretary

E: furlonga@liveprool.ac.uk
T: 0151 795 4358

8.6 Appendix 6: Student data collecting form

Advanced Endodontic Course Data Collection

Group 1

Student seat number	

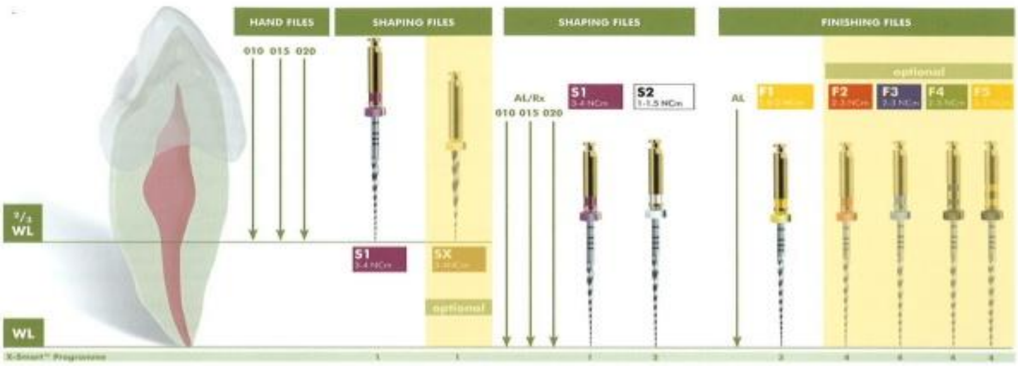
Please ensure that this number tallies with the numbering on your blocks

How many canals have you prepared on the clinic prior to this course?	
Can you state how many of these were prepared with hand protaper?	
If not all with protaper what other preparation method was used ?	

Preparation Type	Was the block prepared successfully without procedural error? (tick= yes, cross=no)	Preparation time (please record in minutes)	If not please tick the errors) which occured	Ledge	apical zip	separation	canal transportation	over preparation	Please record details of any error(s), in particular the file which created the error(s), it's position and the consequence of this error in block preparation (i.e. Could the instrument/ledge be bypassed? Did you need to start a new block?) please keep all blocks if you need to prepare another

8.7 Appendix 7: PTU preparation protocol

ProTaper® Universal Protocol



ProTaper® Universal Sequence (use at 250rpm)

- Fill pulp chamber with sodium hypochlorite
- Explore canal passively with ISO 010 FlexoFile (watch-winding action) to 2/3 of the estimated working length (EWL) as determined from a pre-op radiograph
- Repeat with 015 and 020 Flexofiles to create a glide path
- Use a lubricant such as Glyde™
- Irrigate between each file

- Use shaper file S1
- Use a 'brushing motion' until depth of the 020 is reached
- Recapitulate once or twice
- (Brushing motion: Take instrument to point of light resistance and "brush" out of the canal)

- If necessary, use SX passively in 'brushing motion': improves straight line access & relocates canal away from furcation.
- Re-irrigate

- Negotiate to EWL with a suitable Flexofile
- Establish potency
- Determine working length (WL) using the Ray-pex 5® apex locator (AL)
- Confirm radiographically (Rx)
- Take 015 and 020 to same length to confirm glide path

- Irrigate & use S1 to WL
- Re-irrigate & take S2 to WL (should go with ease)
- Re-confirm WL using Ray-pex 5®

- Irrigate & use Finishing file F1 (020), to WL & immediately withdraw
- Gauge apical foramen with 020 Flexofile
- If snug, obturate (ProTaper® Universal GP or Obturators)
- If loose, use F2 (025) and when necessary use F3/F4/F5 (030, 040 & 050)
- Irrigate & take a 010 Flexofile to WL to remove debris and ensure potency

- Finishing files are used in a straight in & out action (NOT brushing).

ProTaper® Universal Guidelines and Pack Details:

ProTaper® Universal NiTi files economically combine speed, quality, simplicity and safety for shaping of root canals with both rotary files and hand files.

ProTaper® Universal Rules:

- ProTaper® rotary files should be used at a constant speed between 150rpm and 350rpm (recommended: 250 rpm)
- The rotary files should be used in a specific endodontic motor with torque control such as the X-Smart™ Motor
- Always irrigate the canal before engaging a file
- Once working length is confirmed, use each file progressively down to the working length
- Use the shaping files (S1, S2 and SX) with a brushing motion. Brushing motion: Take the file passively to the point of light resistance and 'brush' out of the canal.
- Use the finishing files (F1-F5) in a 'in and out' action (not brushing)
- Withdraw the files once working length is reached
- Clean the files directly after use

ProTaper® Universal Product Details:

ProTaper® Universal treatment files:

Available pack options:

- Starter pack (1x each of the following: S1, SX, S2, F1, F2 & F3)
- Three essentials pack (2 x each of the following: S1, S2 & F1)
- Individual refill packs (x6 files)

Available Lengths:

- 21mm, 25mm & 31mm
- (SX is 19mm)

Products in the ProTaper® Universal range include colour-coded:

- ProTaper® rotary treatment files
- ProTaper® for Hand Use treatment files
- ProTaper® paper points
- ProTaper® gutta percha points
- ProTaper® Thermafil Obturators
- ProTaper® re-treatment files (D1, D2 & D3)

Recommended hand file options for finding your glide path:

Calcified canals: C+Files:

- Ideal for finding a glide path in calcified or difficult to negotiate root canals
- Available in ISO sizes 008, 010 and 015
- Available in lengths 18mm, 21mm and 25mm

Senseus ProFinders:

- An alternative to using K-Flexofiles with a unique dual-taper for increased flexibility and easy penetration into the root canal
- Silcione handle for increased comfort and tactile feedback
- Available in ISO sizes 010, 013 and 017
- Available in lengths 18mm, 21mm and 25mm

K-Flexofiles:

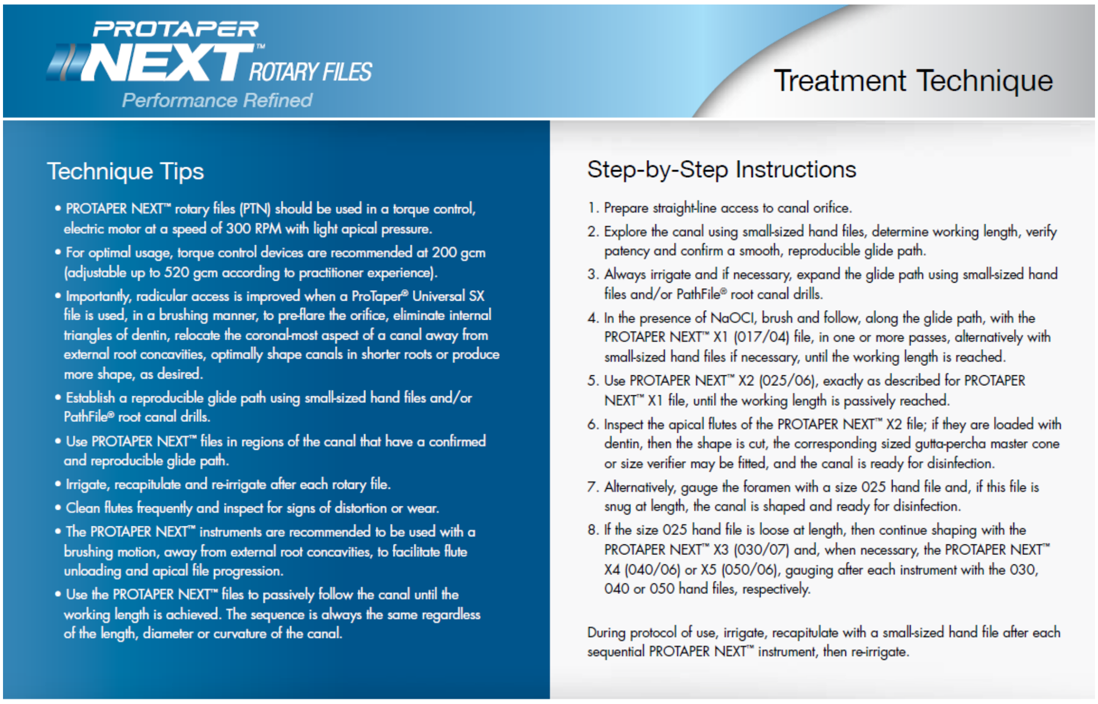
- High quality stainless steel files
- Available in ISO sizes 008- 140
- Available in lengths 21mm, 25mm and 31mm

DENTSPLY Limited Building 1, Aviator Park Station Road, ADDLESTONE, KT15 2PG

Telephone +44 (0)1932 853422 (Endodontic)
Or visit www.dentsply.co.uk I www.dentsply.com

For better dentistry

8.8 Appendix 8: PTN preparation protocol



PROTAPER NEXT™ ROTARY FILES
Performance Refined

Treatment Technique

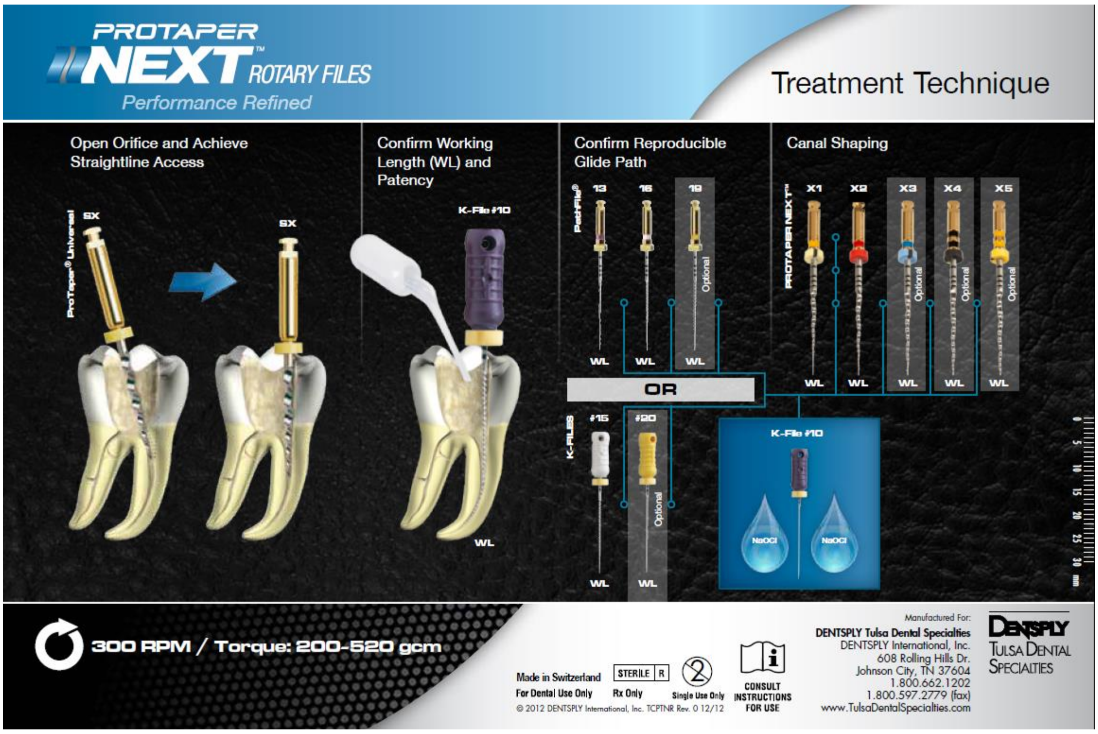
Technique Tips

- PROTAPER NEXT™ rotary files (PTN) should be used in a torque control, electric motor at a speed of 300 RPM with light apical pressure.
- For optimal usage, torque control devices are recommended at 200 gcm (adjustable up to 520 gcm according to practitioner experience).
- Importantly, radicular access is improved when a ProTaper® Universal SX file is used, in a brushing manner, to pre-flare the orifice, eliminate internal triangles of dentin, relocate the coronal-most aspect of a canal away from external root concavities, optimally shape canals in shorter roots or produce more shape, as desired.
- Establish a reproducible glide path using small-sized hand files and/or PathFile® root canal drills.
- Use PROTAPER NEXT™ files in regions of the canal that have a confirmed and reproducible glide path.
- Irrigate, recapitulate and re-irrigate after each rotary file.
- Clean flutes frequently and inspect for signs of distortion or wear.
- The PROTAPER NEXT™ instruments are recommended to be used with a brushing motion, away from external root concavities, to facilitate flute unloading and apical file progression.
- Use the PROTAPER NEXT™ files to passively follow the canal until the working length is achieved. The sequence is always the same regardless of the length, diameter or curvature of the canal.

Step-by-Step Instructions

1. Prepare straight-line access to canal orifice.
2. Explore the canal using small-sized hand files, determine working length, verify patency and confirm a smooth, reproducible glide path.
3. Always irrigate and if necessary, expand the glide path using small-sized hand files and/or PathFile® root canal drills.
4. In the presence of NaOCl, brush and follow, along the glide path, with the PROTAPER NEXT™ X1 (017/04) file, in one or more passes, alternatively with small-sized hand files if necessary, until the working length is reached.
5. Use PROTAPER NEXT™ X2 (025/06), exactly as described for PROTAPER NEXT™ X1 file, until the working length is passively reached.
6. Inspect the apical flutes of the PROTAPER NEXT™ X2 file; if they are loaded with dentin, then the shape is cut, the corresponding sized gutta-percha master cone or size verifier may be fitted, and the canal is ready for disinfection.
7. Alternatively, gauge the foramen with a size 025 hand file and, if this file is snug at length, the canal is shaped and ready for disinfection.
8. If the size 025 hand file is loose at length, then continue shaping with the PROTAPER NEXT™ X3 (030/07) and, when necessary, the PROTAPER NEXT™ X4 (040/06) or X5 (050/06), gauging after each instrument with the 030, 040 or 050 hand files, respectively.

During protocol of use, irrigate, recapitulate with a small-sized hand file after each sequential PROTAPER NEXT™ instrument, then re-irrigate.



8.9 Appendix 9: XPS preparation protocol:

FKG swiss endo

XP-endo® Shaper

Protocol
Protocole
Protokoll

www.fkg.ch

STERILE R

► Golden rules

800 rpm
1 Ncm

- Prior to using the XP-endo® Shaper, establish glide path to at least 15/.02.
- In multirooted teeth, begin with the largest canal.
- Never force the instrument.
- Irrigate copiously throughout the instrumentation protocol.

► Règles d'or

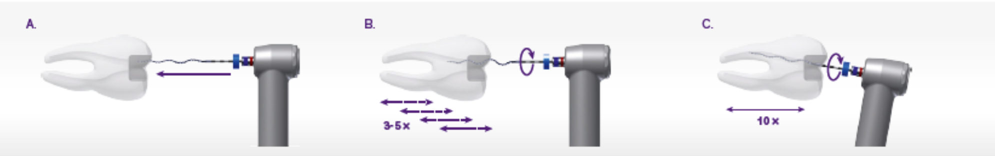
800 tr/min
1 Ncm

- Avant l'utilisation du XP-endo® Shaper, réaliser un cathétérisme d'au minimum 15/.02.
- Dans des dents pluriradiculées, débuter par le canal le plus large.
- Ne jamais forcer l'instrument.
- Irriguer abondamment pendant tout le protocole.

► Goldene Regeln

800 1/min
1 Ncm

- Vor der Verwendung des XP-endo® Shaper einen Gleitpfad von mindestens 15/.02 erstellen.
- In einem Zahn mit mehreren Kanälen mit dem weitesten Kanal beginnen.
- Niemals Druck auf das Instrument ausüben.
- Während des gesamten Protokolls ausgiebig spülen.



► Protocol

800 rpm (800-1000)
1 Ncm

1. Prior to using the XP-endo® Shaper, establish glide path to at least 15/.02. *In calcified/constricted canals or complex curvatures, a glide path to 10/.04 is recommended.*
2. Insert the tip of the XP-endo® Shaper into the canal (Fig. A), retract slightly and engage the handpiece in rotation mode. *The canal and the pulp chamber should always contain irrigant.*
3. Use gentle strokes to progress down to working length (WL) (Fig. B); disengage after each stroke. If WL is not reached in 3 to 5 strokes, stop, irrigate, recapitulate and proceed again with XP-endo® Shaper. *Never force the instrument and always keep it spinning and moving while in the canal.*
4. Once WL is reached, irrigate and work the instrument in long in and out gentle movements to WL for another 10 strokes (Fig. C). The final apical dimension is now at least 30/.04.
5. Irrigate the canal in order to eliminate suspended debris.
6. Confirm the final apical dimension with a 30/.04 gutta percha point.
7. If a larger preparation is required, use an appropriate Race instrument to obtain the desired final preparation.
8. Apply your regular irrigation protocol. *Final cleaning with XP-endo® Finisher is recommended.*
9. Obturate with gutta percha and sealer. *TotalFill® BC Points™ and TotalFill® BC Sealer™ are recommended.*

► Protocole

800 tr/min (800-1000)
1 Ncm

1. Avant d'utiliser le XP-endo® Shaper, réaliser un cathétérisme d'au minimum 15/.02. *En cas de canaux calcifiés/étroits ou de courbures complexes, un cathétérisme à 10/.04 est recommandé.*
2. Introduire la pointe du XP-endo® Shaper à l'intérieur du canal (Fig. A.), le retirer légèrement et enclencher la rotation. *Le canal et la chambre pulpaire doivent toujours contenir de l'irrigant.*
3. A l'aide de légers mouvements de va-et-vient, progresser jusqu'à la longueur de travail (LT) (Fig. B); désengager après chaque mouvements. Si la LT n'est pas atteinte en 3 à 5 mouvements, arrêter, irriguer, vérifier la perméabilité et recommencer. *Ne jamais forcer l'instrument et toujours le maintenir en rotation et en mouvement dans le canal.*
4. Une fois la LT atteinte, irriguer et effectuer 10 longs et légers mouvements de va-et-vient supplémentaires (Fig. C). La dimension apicale finale est maintenant d'au minimum 30/.04.
5. Irriguer le canal afin d'éliminer les débris en suspension.
6. Confirmer la dimension apicale finale avec un cône de gutta-percha 30/.04.
7. Si une préparation plus large est nécessaire, utiliser un instrument Race approprié afin d'obtenir la préparation finale désirée.
8. Appliquer votre protocole d'irrigation habituel. *XP-endo® Finisher est recommandé pour le nettoyage final.*
9. Obturer avec de la gutta-percha et du ciment. *TotalFill® BC Points™ et TotalFill® BC Sealer™ sont recommandés.*

► Protokoll

800 1/min (800-1000)
1 Ncm

1. Vor der Verwendung des XP-endo® Shaper einen Gleitpfad von mindestens 15/.02 erstellen. *Bei engen/verkalkten Kanälen oder starken Krümmungen wird ein Gleitpfad von 10/.04 empfohlen.*
2. Die Spitze des XP-endo® Shaper in den Kanal einführen (Abb. A), etwas zurückziehen und die Rotation des Handstücks starten. *Der Kanal und das Pulpakavum müssen immer mit Spülflüssigkeit gefüllt sein.*
3. Mit sanften Ein- und Auswärtsbewegungen aufbereiten, bis die Arbeitslänge (AL) erreicht ist (Abb. B); nach jeder Bewegung Instrument entlasten. Falls die AL nach 3 bis 5 Ein- und Auswärtsbewegungen nicht erreicht ist, stoppen, spülen und wiederholen. *Niemals Druck auf das Instrument ausüben und es im Kanal stets in Bewegung halten.*
4. Wenn die AL erreicht ist, erneut spülen und mit dem Instrument nochmals 10 lange, sanfte Ein- und Auswärtsbewegungen bis auf AL ausführen (Abb. C). Die minimale apikale Aufbereitung ist nun normalerweise mindestens 30/.04.
5. Den Kanal spülen, um Debris zu entfernen.
6. Die Grösse der Aufbereitung mit einer 30/.04 Guttapercha-spitze prüfen.
7. Wird eine größere Aufbereitung gewünscht, ein entsprechendes Race Instrument verwenden, um die gewünschte Größe zu erreichen.
8. Das übliche Spülprotokoll anwenden. *Wir empfehlen die finale Reinigung mit dem XP-endo® Finisher.*
9. Mit Guttapercha und Sealer füllen. *Wir empfehlen TotalFill® BC Points™ und TotalFill® BC Sealer™.*

FKG REF. 99.100.10.06A.XX_REV2_2017-05 - © FKG Dentaire SA

CE 0120

8.10 Appendix 10: XPF preparation protocol:

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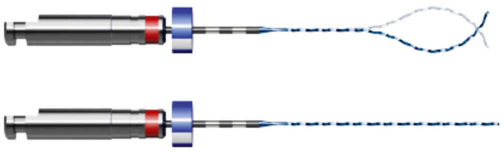
XP-endo Finisher

Protocol
Protocole
Protokoll



STERILE R

► Golden rules

800 rpm
1 Ncm

- XP-endo Finisher must only be used only after preparing the canal to at least #25;
- In multirooted teeth, begin with the largest canal;
- The access cavity must be filled with irrigant only after inserting the XP-endo Finisher into the canal.

► Règles d'or

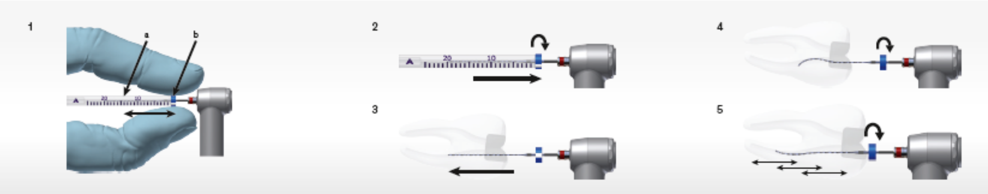
800 tr/min
1 Ncm

- XP-endo Finisher doit être utilisé uniquement après une préparation canalaire d'au moins #25;
- Dans des dents pluriradiculaires, débuter par le canal le plus large;
- La cavité d'accès doit être remplie avec de l'irrigant seulement après avoir inséré le XP-endo Finisher dans le canal.

► Goldene Regeln

800 Upm
1 Ncm

- XP-endo Finisher darf ausschließlich nach einer Aufbereitung bis mindestens #25 verwendet werden;
- In einem Zahn mit mehreren Kanälen mit dem weitesten Kanal beginnen;
- Die Zugangskavität darf erst mit Spülflüssigkeit gefüllt werden, nachdem XP-endo Finisher in den Kanal eingeführt ist.



► Protocol

800 rpm (800-1000)
1 Ncm

- Set the working length by positioning the rubber stop (b) using the plastic tube (a) (Figure 1).
- Cool the XP-endo Finisher with a cooling spray via the tube.
- Switch the XP-endo Finisher to rotate mode, and press against the side walls as you remove it from the tube, to ensure that the file is straight (Figure 2). Then deactivate rotate mode.
- Insert the straightened XP-endo Finisher into the first tooth canal (Figure 3) and, once the tip has been inserted, activate rotate mode (Figure 4). Add some irrigant to the access cavity.
- Use the XP-endo Finisher for approximately one minute, applying slow, gentle longitudinal movements of 7-8 mm, so as to cover the entire length of the canal (Figure 5). Press the instrument against the side walls of the canals during the procedure. Make sure to stay inside the canal.
- After one minute, remove the XP-endo Finisher from the canal, still in rotation mode.

► Protocole

800 tr/min (800-1000)
1 Ncm

- Définir la longueur de travail en positionnant le rubber stop (b) à l'aide du tube en plastique (a) (Figure 1).
- Refroidir le XP-endo Finisher à travers le tube à l'aide d'un spray de refroidissement.
- Mettre le XP-endo Finisher en rotation et le sortir du tube en appliquant un appui contre les parois latérales afin d'assurer la rectitude de la lime (Figure 2). Arrêter ensuite la rotation.
- Introduire le XP-endo Finisher redressé dans le premier canal de la dent (Figure 3) et, une fois que le pointe est introduite, le mettre en rotation (Figure 4). Ajouter de l'irrigant dans la cavité d'accès.
- Utiliser le XP-endo Finisher pendant environ une minute en effectuant de lents et doux mouvements longitudinaux de 7-8 mm, de manière à traiter toute la longueur du canal (Figure 5). Appuyer l'instrument contre les parois latérales des canaux durant la procédure. Faire attention à bien rester à l'intérieur du canal.
- Après une minute, sortir le XP-endo Finisher du canal pendant qu'il est en rotation.

► Protokoll

800 Upm (800-1000)
1 Ncm

- Zur Einstellung der Arbeitslänge mithilfe des Kunststoff-Röhrchens (a) den Gummistopp (b) verschieben (Abb. 1).
- XP-endo Finisher durch das Röhrchen mit Kältespray abkühlen.
- XP-endo Finisher in Rotation versetzen und unter gleichzeitigem Drücken auf die Seitenwände aus dem Kunststoff-Röhrchen herausnehmen, um sicherzustellen, dass das Instrument gerade bleibt (Abb. 2). Rotation stoppen.
- Geraden XP-endo Finisher in den ersten Kanal des Zahns einführen (Abb. 3). Rotation starten, sobald die Spitze im Kanal ist (Abb. 4). Zugangskavität mit Spülflüssigkeit füllen.
- XP-endo Finisher etwa eine Minute anwenden. Das Instrument 7–8 mm der Länge nach langsam und sanft bewegen, um die gesamte Länge des Kanals zu behandeln (Abb. 5). Dabei Druck gegen die Kanalwände ausüben und gut darauf achten, das Instrument im Kanal zu belassen.
- XP-endo Finisher nach einer Minute rotierend aus dem Kanal entfernen.

FKG REF: 99.X00.10.02B.XX - 03/2016
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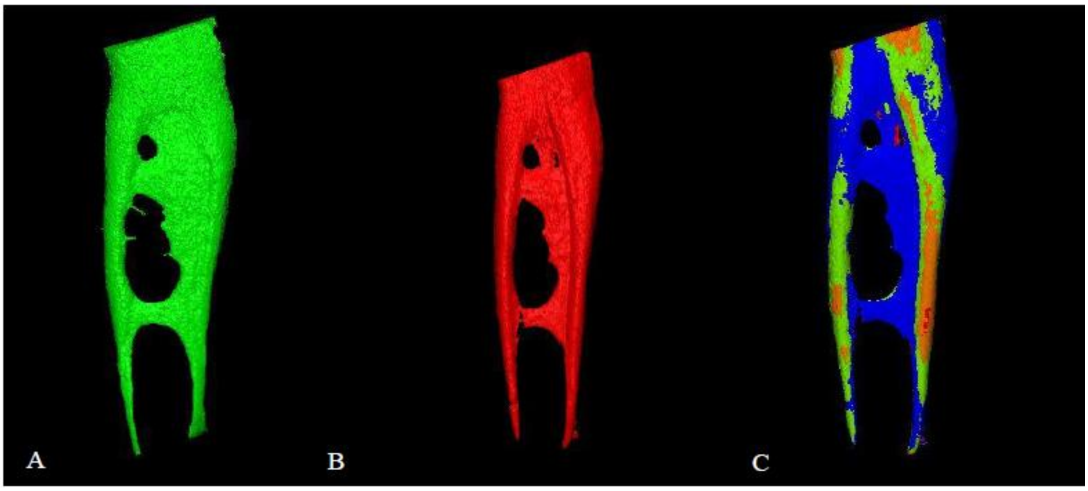
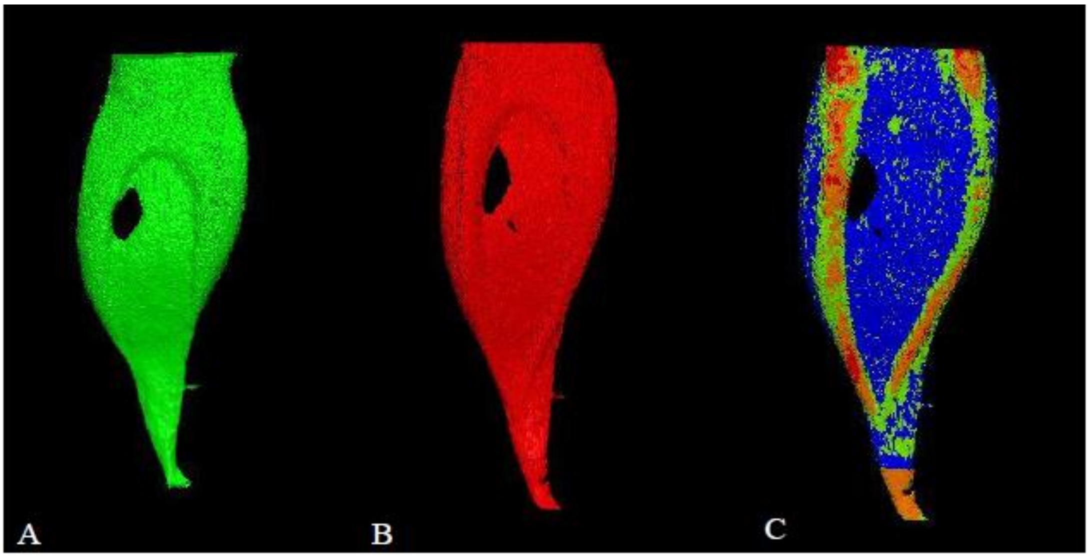
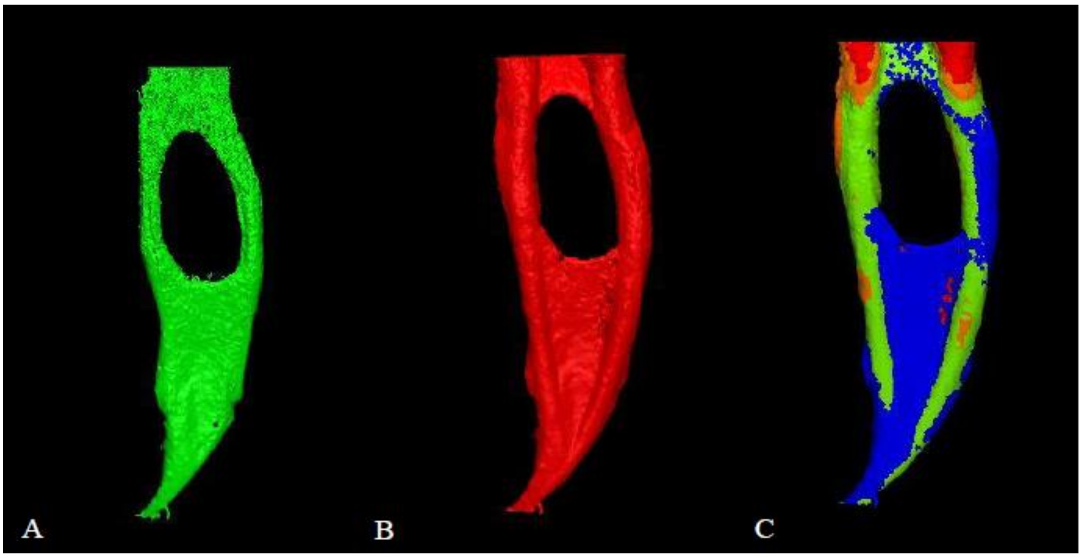
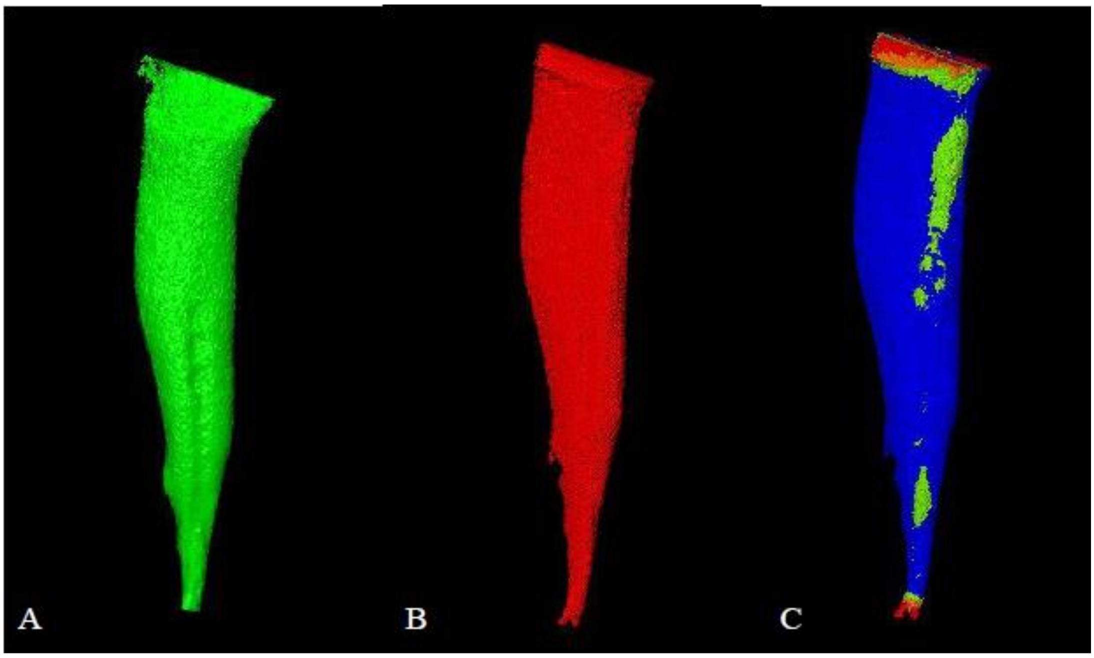
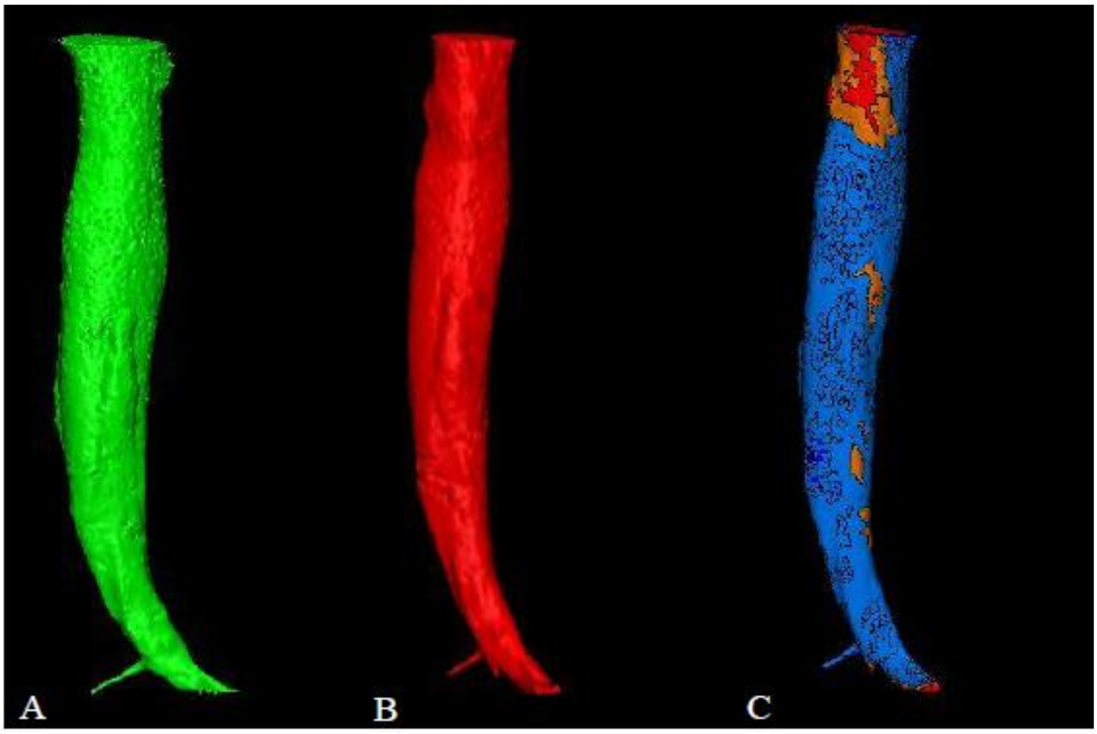
8.11 Appendix 11: Images of root canal space analysis








A
B
C


A
B
C

8.12 Appendix 12: SPSS output

Univariate Analysis of Variance

Notes

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	Cases Used	Statistics are based on all cases with valid data for all variables in the model.
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Page 1

Between-Subjects Factors

		Value Label	N
File System	1	XPS	22
	2	PTN	21
Canal Type	1	Mesial	21
	2	Distal	22

Descriptive Statistics

Dependent Variable: % of Instr. XPF

File System	Canal Type	Mean	Std. Deviation	N
XPS	Mesial	5.45%	3.417%	11
	Distal	6.73%	5.350%	11
	Total	6.09%	4.428%	22
PTN	Mesial	5.90%	5.021%	10
	Distal	5.55%	5.663%	11
	Total	5.71%	5.236%	21
Total	Mesial	5.67%	4.151%	21
	Distal	6.14%	5.410%	22
	Total	5.91%	4.785%	43

Tests of Between-Subjects Effects

Dependent Variable: % of Instr. XPF

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	24.435[a]	3	8.145	.339	.797
Intercept	538.010	1	538.010	22.389	.000
FileSystem	7.076	1	7.076	.294	.590
CanalType	7.440	1	7.440	.310	.581
PreOPVol	20.448	1	20.448	.851	.362
Error	937.192	39	24.031		
Total	2462.000	43			
Corrected Total	961.628	42			

a. R Squared = .025 (Adjusted R Squared = -.050)

Estimated Marginal Means

1. File System

Dependent Variable: % of Instr. XPF

File System	Mean	Std. Error	95% Confidence Interval Lower Bound	Upper Bound
XPS	6.316[a]	1.073	4.145	8.486
PTN	5.458[a]	1.103	3.228	7.689

a. Covariates appearing in the model are evaluated at the following values: PreOP Vol. = 856951.58.

2. Canal Type

Dependent Variable: % of Instr. XPF

Canal Type	Mean	Std. Error	95% Confidence Interval Lower Bound	Upper Bound
Mesial	5.455[a]	1.093	3.245	7.665
Distal	6.319[a]	1.064	4.167	8.471

a. Covariates appearing in the model are evaluated at the following values: PreOP Vol. = 856951.58.

```
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  /INTERCEPT=INCLUDE
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Univariate Analysis of Variance

Notes

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	Cases Used	Statistics are based on all cases with valid data for all variables in the model.
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Between-Subjects Factors

		Value Label	N
File System	1	XPS	11
	2	PTN	12
Canal Type	2	Distal	23

Descriptive Statistics

Dependent Variable: Diff.in.Vol.Coronal.Distal

File System	Canal Type	Mean	Std. Deviation	N
XPS	Distal	149872.8182	84923.50636	11
	Total	149872.8182	84923.50636	11
PTN	Distal	415650.7500	518717.0760	12
	Total	415650.7500	518717.0760	12
Total	Distal	288539.5652	395271.0030	23
	Total	288539.5652	395271.0030	23

Tests of Between-Subjects Effects

Dependent Variable: Diff.in.Vol.Coronal.Distal

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	5.706E+11[a]	2	2.853E+11	1.990	.163
Intercept	9.742E+11	1	9.742E+11	6.797	.017
FileSystem	2.400E+11	1	2.400E+11	1.675	.210
CanalType	.000	0	.	.	.
PreOPVol	1.652E+11	1	1.652E+11	1.153	.296
Error	2.867E+12	20	1.433E+11		
Total	5.352E+12	23			
Corrected Total	3.437E+12	22			

a. R Squared = .166 (Adjusted R Squared = .083)

Estimated Marginal Means

1. File System

Dependent Variable: Diff.in.Vol.Coronal.Distal

File System	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
XPS	176954.189[a]	116904.341	-66903.994	420812.371
PTN	390826.160[a]	111710.030	157803.122	623849.199

a. Covariates appearing in the model are evaluated at the following values: PreOP Vol. = 996566.77.

2. Canal Type

Dependent Variable: Diff.in.Vol.Coronal.Distal

Canal Type	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Distal	283890.175[a]	79023.958	119049.086	448731.263

a. Covariates appearing in the model are evaluated at the following values: PreOP Vol. = 996566.77.

Univariate Analysis of Variance

Between-Subjects Factors

		Value Label	N
File System	1	XPS	22
	2	PTN	22
Canal Type	1	Mesial	21
	2	Distal	23

Notes

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Missing Value Handling	Definition of Missing	User-defined missing values are treated as missing.
	Cases Used	Statistics are based on all cases with valid data for all variables in the model.
Syntax		UNIANOVA ofInstru BY FileSystem CanalType WITH PreOPVol /METHOD=SSTYPE(3) /INTERCEPT=INCLUDE /EMMEANS=TABLES (FileSystem) WITH (PreOPVol=MEAN) /EMMEANS=TABLES (CanalType) WITH (PreOPVol=MEAN) /PRINT=DESCRIPTIVE /CRITERIA=ALPHA(.05) /DESIGN=FileSystem CanalType PreOPVol.
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Between-Subjects Factors

		Value Label	N
File System	1	XPS	22
	2	PTN	22
Canal Type	1	Mesial	21
	2	Distal	23

Univariate Analysis of Variance

Notes

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Missing Value Handling	Definition of Missing	User-defined missing values are treated as missing.
	Cases Used	Statistics are based on all cases with valid data for all variables in the model.

Notes

Syntax		UNIANOVA Diff.inVol BY FileSystem CanalType WITH PreOPVol /METHOD=SSTYPE(3) /INTERCEPT=INCLUDE /EMMEANS=TABLES (FileSystem) WITH (PreOPVol=MEAN) /EMMEANS=TABLES (CanalType) WITH (PreOPVol=MEAN) /PRINT=DESCRIPTIVE /CRITERIA=ALPHA(.05) /DESIGN=FileSystem CanalType PreOPVol.
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Between-Subjects Factors

		Value Label	N
File System	1	XPS	22
	2	PTN	22
Canal Type	1	Mesial	21
	2	Distal	23

Descriptive Statistics

Dependent Variable: Diff. in Vol.

File System	Canal Type	Mean	Std. Deviation	N
XPS	Mesial	274824.43	193812.544	11
	Distal	143622.16	124368.501	11
	Total	209223.30	172514.384	22
PTN	Mesial	482904.78	209184.144	10
	Distal	282400.16	323476.166	12
	Total	373538.62	289836.686	22
Total	Mesial	373910.31	223187.269	21
	Distal	216028.07	253718.902	23
	Total	291380.96	249934.487	44

Tests of Between-Subjects Effects

Dependent Variable: Diff. in Vol.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	6.263E+11[a]	3	2.088E+11	4.054	.013
Intercept	1.237E+12	1	1.237E+12	24.015	.000
FileSystem	2.398E+11	1	2.398E+11	4.657	.037
CanalType	2.282E+11	1	2.282E+11	4.432	.042
PreOPVol	2.850E+10	1	2.850E+10	.553	.461
Error	2.060E+12	40	5.149E+10		
Total	6.422E+12	44			
Corrected Total	2.686E+12	43			

a. R Squared = .233 (Adjusted R Squared = .176)

Estimated Marginal Means

1. File System

Dependent Variable: Diff. in Vol.

File System	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
XPS	217124.656[a]	49532.612	117015.513	317233.799
PTN	372481.038[a]	49836.810	271757.089	473204.988

a. Covariates appearing in the model are evaluated at the following values: PreOP Vol. = 865174.79.

2. Canal Type

Dependent Variable: Diff. in Vol.

Canal Type	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
Mesial	370084.406[a]	50676.042	267664.305	472504.508
Distal	219521.288[a]	48327.500	121847.767	317194.809

a. Covariates appearing in the model are evaluated at the following values: PreOP Vol. = 865174.79.

Univariate Analysis of Variance

Notes

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	Cases Used	Statistics are based on all cases with valid data for all variables in the model.
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Between-Subjects Factors

		Value Label	N
File System	1	XPS	22
	2	PTN	22
Canal Type	1	Mesial	21
	2	Distal	23

Descriptive Statistics

Dependent Variable: Diff. in Vol. Coronal

File System	Canal Type	Mean	Std. Deviation	N
XPS	Mesial	297019.73	162492.206	11
	Distal	149872.82	84923.506	11
	Total	223446.27	147235.536	22
PTN	Mesial	392748.90	308278.950	10
	Distal	415650.75	518717.076	12
	Total	405240.82	426387.122	22
Total	Mesial	342605.05	241594.977	21
	Distal	288539.57	395271.003	23
	Total	314343.55	328375.555	44

Tests of Between-Subjects Effects

Dependent Variable: Diff. in Vol. Coronal

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	5.652E+11[a]	3	1.884E+11	1.851	.153
Intercept	1.903E+12	1	1.903E+12	18.692	.000
FileSystem	2.109E+11	1	2.109E+11	2.072	.158
CanalType	7181213739	1	7181213739	.071	.792
PreOPVol	1.589E+11	1	1.589E+11	1.561	.219
Error	4.072E+12	40	1.018E+11		
Total	8.984E+12	44			
Corrected Total	4.637E+12	43			

a. R Squared = .122 (Adjusted R Squared = .056)

Estimated Marginal Means

1. File System

Dependent Variable: Diff. in Vol. Coronal

File System	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
XPS	242104.298[a]	69639.742	101357.128	382851.467
PTN	387796.827[a]	70067.425	246185.278	529408.375

a. Covariates appearing in the model are evaluated at the following values: PreOP Vol. = 865174.79.

2. Canal Type

Dependent Variable: Diff. in Vol. Coronal

Canal Type	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
Mesial	328304.930[a]	71247.333	184308.698	472301.162
Distal	301596.194[a]	67945.431	164273.356	438919.032

a. Covariates appearing in the model are evaluated at the following values: PreOP Vol. = 865174.79.